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SUMMIT AND SOUTH SLOPE OF MAUNA KEA

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GENERAL FEATURES AND GLACIAL GEOLOGY OF MAUNA KEA, HAWAII

BY HERBERT E. GREGORY AND CHESTER K. WENTWORTH

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INTRODUCTION

The four volcanic masses whose coalescing bases form the island of Hawaii are substantially alike in petrographic composition; all of them bear cinder cones on their flanks, and lava flows from all of them have extended far into the sea, and also inland to join their neighbors. As

regards their topographic expression, they form two groups. Mauna Loa and Hualalai have remarkably flat, smooth profiles and summit craters; Mauna Kea and Kohala are rugged masses sharply incised by canyons and have no topographic feature to indicate the major source of the materials of which they are constructed. The two giant domes, Mauna Loa and Mauna Kea, reveal these differences clearly.

The profile of Mauna Loa extends from the coast as an almost unbroken curve with a gradient averaging about 600 feet to the mile nearly to the rim of the active crater, Mokuaweoweo, at an altitude of 13,680 feet.[1] Mauna Kea, only 25 miles distant, rises from a base about half as large as that of Mauna Loa and reaches an altitude 104 feet higher (13,784 feet). Its profile is a series of broken, irregularly placed steps which lead to a summit plateau with an area of about 10 square miles, a plateau made uneven by cinder cones rising above its surface and by gorges cut below it. The ascent of Mauna Loa from the hotel at Kilauea involves the traverse of a slope of lava sufficiently fresh to retain its original structure and over a trail which might readily be converted into an automobile road. All routes to the summit of Mauna Kea wind in and out among foothills, follow and cross gorges with alternating stretches of "good going" and "stiff climbs". Up to about 11,500 feet in the valleys, and to about 12,500 feet on the flat divides, the rock where exposed is much weathered and the soil in places is deep. The plateau is covered with red and brown lapilli, partly decomposed blocks and bombs of lava and with ridges and flats of angular, fresh blocks and slabs of dense basalt. Particularly in the valleys and on the flanks of rock-ridges this material is so continuous, so deeply piled, and presents such sharp edges as to make travel on horseback hazardous.

Mauna Loa is an active volcano and any traces of glacial action which may have taken place at its summit during Pleistocene time have, so far as known, been effaced by subsequent lava flows. Mauna Kea, on the contrary, has long been dormant and shows evidence of little post-Wisconsin volcanic activity. Hence it is the only place in Hawaii, and probably in the entire central Pacific, where a record of Pleistocene glaciation can be found. The mountain is therefore of peculiar interest to geologists, and to geographers and biologists as well.

HISTORICAL SKETCH

That the Hawaians were familiar with the summit of Mauna Kea is amply demonstrated by adz quarries at Keanakakoi (cave of the adz makers), by walls, stone platforms, and burial caves. The first recorded ascent of the mountain was by Goodrich[2] in August 1823. In

[1] Elevations based on U. S. Geol. Survey topographic surveys, completed 1930.

[2] Joseph Goodrich: in *Letters to the Editor*, Am. Jour. Sci., 1st ser., vol. 16 (1829) p. 345-350; vol. 25 (1833) p. 199-201.

describing a subsequent ascent in December 1832, he speaks of "fragments of granite embedded in lava—specimens of compact lava resembling hornstone—some specimens of granite a foot or more in diameter." He found near the summit a "lake or pond of water—75 rods in circumference, or 25 in diameter—half frozen over . . . very deep."

James Macrae,[3] botanist of the *Blonde*, who spent many uncomfortable hours on top of Mauna Kea, June 15-17, 1825, noted "lava and sand intermixed with small broken stones about the size of brickbats—large, sharp-edged granite stones of several tons weight, which have beyond a doubt been thrown up by some previous convulsion."

David Douglas,[4] who ascended Mauna Kea, January 10, 1834, describes the top of Mauna Kea as a "tableland or platform where spring the great vent holes of the subterranean fire or numerous volcanoes . . . large blocks of lava of every shape, size and color . . . in some places the round boulders of lava are so irregularly placed and the sand so washed among them as to give the appearance of a causeway."

Charles Pickering[5] and William D. Brackenridge with a guide, "Dawson, alias Billy-Lilly," ascended Mauna Kea in 1841. They speak of "a plain made desolate by stones, gravel, sand, scoria . . . resembled the dry bed of some great river over which the water has passed for ages—no appearance of lava streams or clinkers—."

Dutton[6] noted the salient physiographic features of Mauna Kea during a day spent on the upper slopes in 1882. He writes:[7]

"After seven hours of travel without a halt, we reached what may be termed the summit platform, which has an altitude . . . averaging probably 12,500 feet. . . . Upon this platform stand about a dozen large cinder-cones, from 700 to 1,000 feet in height, carrying the extreme apices of the mountain very nearly 14,000 feet. . . . The aspect of the lavas beneath our feet now becomes somewhat different from those seen lower down the mountain. They are lighter colored and some of them are much more compact. . . . Hard by the noon-day camp is a mass of very light-colored lava which seems at first to have a constitution notably different from the very black almost ultra basalts to which we have thus far been accustomed. It is exceedingly compact and fine grained and has a very light gray color. No signs of any recent volcanic activity are to be seen. . . . How these lava sheets have thus been torn to pieces, as it were, and reduced to piles of moldering ruins I can explain only by suggesting the action of frost and ice filling the cracks and wedging the pieces apart by expansion. . . . A few hundred yards from our noon camp is the head of a ravine which has been scored to a considerable depth by the unmistakable action of running water."

Hitchcock,[8] who ascended the mountain in 1886, mentions "many canyons about the base of Mauna Kea" as "criteria of a greater age" and

[3] W. F. Wilson: *With Lord Byron at the Sandwich Islands in 1825, being extracts from the diary of James Macrae* (1922). Honolulu.

[4] W. F. Wilson [Compiler]: *David Douglas* [in his note book], *Botanist at Hawaii* (1919). Honolulu.

[5] Charles Wilkes: *Narrative of the United States Exploring Expedition*, vol. 4 (1845) p. 202-203.

[6] C. E. Dutton: *Hawaiian volcanoes*, U. S. Geol. Surv., 4th Ann. Rept. (1884) p. 161-164.

[7] Dutton arrived in Honolulu, May 11, 1882, and spent "nearly four months" on Hawaii. His trip to Mauna Kea was probably in July or August.

[8] C. H. Hitchcock: *Hawaii and its volcanoes* (1909). Honolulu.

states that "there is a sort of plateau upon the higher part of Mauna Kea above the contour of 12,500 feet with an area of from 35 to 40 square miles." The Mauna Kea summit cones are usually "perfect" [not breached] . . . one "cone at the summit is covered by blocks of consolidated lava including many bombs." A lake about 200 feet long and 150 feet wide "occupies a small crater between two sand cones".

Baldwin,[9] while establishing a triangulation station on Mauna Kea in 1889, observed that the "sides of the mountain [are] made up mostly of disintegrated aa flows and sand cones . . . on top the texture of the scoria is somewhat different being of a light bluish gray color; rings when struck, and splits in regular smooth layers; the feldspars being present in large quantities."

Bryan noted that the deep gulches which furrow the northeast side of Mauna Kea do not extend to the summit, and ascribed the difference to the later extinction of volcanic activity at the summit. He says:

> "Its elliptical summit is rather thickly sprinkled with a number of cinder cones: about two dozen being above the 12,500 foot contour line. . . . One of these cones is occupied by a pond 40 feet deep and several acres in extent."[10]

Though Dutton ascribed the fresh angular blocks of compact basalt to "the action of frost and ice", and both Dutton and Bryan called attention to the sudden change in profile of the drainage lines, the first record of unmistakable glacial features on Mauna Kea was made by Daly, who ascended the mountain to the edge of its summit platform in 1909. Daly writes:

> "Hawaii itself seems to have borne at least one small glacier, the characteristic traces of which were observed by the writer on Mauna Kea at the 12,000 foot level."[11]

There have doubtless been many unrecorded visits to the summit of Mauna Kea since Goodrich's traverse in 1823. Indeed, it is probable that fifty or more years ago, when ranch operations were of relatively greater importance and the old Makahalau-Keanakolu trail was in general use as a route from Kawaihae and Waimea to Hilo, the upper slopes of the mountain were more generally known to the residents of Hawaii than they are today. During the last two decades a number of scientists interested in the natural history of Hawaii have reached the summit on single-day trips. Forestry surveys by the Hawaiian Department of Agriculture, topographical surveys by the United States Geological Survey (1925-1927), and observations by T. A. Jaggar and his colleagues

[9] E. D. Baldwin: *A trip to the summit of Mauna Kea*, Hawaiian Ann. for 1890 (1889) p. 54-58. Honolulu.

[10] W. A. Bryan: *Natural history of Hawaii* (1915) p. 151. Honolulu.

[11] R. A. Daly: *Pleistocene glaciation and the coral reef problem*, Am. Jour. Sci., 4th ser., vol. 30 (1910) p. 297. The geology of Mauna Kea is briefly discussed in two other papers by Daly [*Problems of the Pacific*, Am. Jour. Sci., 4th ser., vol. 41 (1916) p. 153-186; *Magmatic differentiation in Hawaii*, Jour. Geol., vol. 19 (1911) p. 297-299].

of the Hawaiian Volcano Research Association have supplied authentic information. In particular, photographs and notes by C. S. Judd and C. J. Kraebel and sketch maps by E. G. Wingate (1927) showing approximately the position of the "new fresh rock" and "old unaltered rock" are contributions of value.

Systematic studies of the glaciation, petrography, and structure of Mauna Kea were made by Gregory and by Wentworth at intervals during the years 1921-1935. On these studies the present report is based. In 1921, Gregory spent seven days (August 5-7, 22-25), and in 1926, three days (July 23-25) on the summit and upper slopes. Awaiting the completion of topographical maps (issued 1932), these observations were recorded in preliminary papers.[12]

Wentworth [13] ascended the mountain in 1929, and as leader of the Mauna Kea Expedition of the Hawaiian Academy of Science spent two weeks of August 1935 in a survey of the summit area, with special attention to glaciation. During the course of this survey, the central summit area was studied in some detail, though only a very general examination of parts of the marginal area of glaciation was made. Even with the convenience of a fixed camp at Lake Waiau, field work at 11,000 to nearly 14,000 feet is arduous for a party coming up abruptly from life at sea level in the tropics. Many problems, particularly those of altering volcanic and glacial activity and of multiple glaciation have scarcely been touched and offer a promising field for more detailed studies.

ACKNOWLEDGMENTS

In the survey of Mauna Kea, cooperation is gratefully acknowledged. Horses and guides were generously provided by Alfred W. Carter, manager of Parker Ranch (1921, 1926, 1935), Donald S. McAllister, manager of Kukaiau Ranch (1921), and David M. Forbes, manager of Kukaiau Ranch (1929). The Mauna Kea Expedition (1935) could not have been carried out without the substantial aid rendered by the Hawaiian Department of the United States Army. All transport and camp arrangements and operations were conducted by a detail of nine enlisted men and non-commissioned officers under the direction of Captain H. A. Meyer. The project was further assisted by the Territorial Division of Forestry, the Territorial Land Office, the Civilian Conservation Corps, the United States Coast Guard, and the Bernice P. Bishop Museum.

[12] H. E. Gregory: *Ice age on Mauna Kea*, Honolulu Advertiser, Sept. (1921); *Glaciation of Mauna Kea*, Third Pacific Sci. Congr. (Tokyo), Pr., vol. 2 (1926) p. 1833.

J. Beyer: *Entdeckung von Spuren diluvialer Vereisung in Hawaii durch Herbert E. Gregory*, in *Die Eiszeit* (1925) p. 132-133.

[13] C. K. Wentworth: *Mauna Kea, White Mountain of Hawaii*, Mid-Pacific Mag., vol. 48 (1935) p. 290-296.

C. K. Wentworth, J. W. Coulter, and C. E. Hartt: *The Mauna Kea Expedition of 1935*, B. P. Bishop Mus., manuscript on file for publication.

GEOGRAPHY

TOPOGRAPHY

The Mauna Kea dome, forming with the Kohala dome the northeastern third of the island of Hawaii, is next younger than the Kohala dome in age. At least its uppermost lava flows overlap the Kohala dome along a curved boundary which extends from the northeast coast at Kukuihaele to the west coast at Kawaihae. In turn, the Mauna Kea dome is overlapped by Mauna Loa lava flows along a similar curved boundary on the south and southwest sides from Hilo to Puako. The saddle of overlap at the north lies at the elevation of about 2,900 feet; that at the south between Mauna Loa and Mauna Kea at 6,600 feet (Fig. 1).

Thus below 6,600 feet, the southern and the western slopes of Mauna Kea are wholly concealed; at the north the Mauna Kea mass is built over and around the Kohala dome and only in the 120-degree sector from N. 20° W. to S. 80° E. are the full slopes accessible from the summit to sea level. Only the upper half of the mountain is involved in this study. Slopes of this part are in general much steeper than those of the exposed northeast lower sector, and the upper half of Mauna Kea has only about one-third the volume of the nearby Mauna Loa above the 7,000-foot contour line. The steepest slopes of the upper half of Mauna Kea on the east are between 9,000 and 10,500 feet, where the gradient is about 1,200 feet a mile. Between 9,000 feet and 6,000 feet, slopes average about 700 feet a mile; below 6,000 feet, less than 500 feet a mile.

On the north side, a maximum gradient of 1,500 feet a mile is found between 7,500 and 10,500 feet, with a gradual reduction to about 500 feet at the 5,000-foot elevation. On the west side there is a pronounced spur around which the contours pass, and down the axis of which the gradient of about 850 feet a mile obtains from 12,000 feet down to 7,000 feet, with a gradual decrease below. In the southwest sector, between 11,000 feet and 7,000 feet, the general gradient is 1,600 feet, with a few small areas as steep as 2,000 feet, a mile. On the south side, toward Humuula, 1,500-foot slopes are found between 9,000 and 11,000 feet. Up to 7,500 feet north and northwest of Humuula is a gently sloping area with gradients of less than 500 feet a mile. The remainder of the south slope is somewhat irregular, with variable slopes among numerous cinder cones.

Above the zone of marked steepening, around the entire mountain, the slope decreases rather abruptly to form a gently domed summit plateau, whose edge may be placed at 11,000, 11,000, 11,500, and 12,000 feet in elevation on the east, north, west, and south sides, respectively. Its surface rises to slightly over 13,000 feet somewhat west of the center, and

on this portion stand the several large cinder cones forming the summit of the mountain (Pl. 1, fig. 1). Above the 7,000-foot level, there are

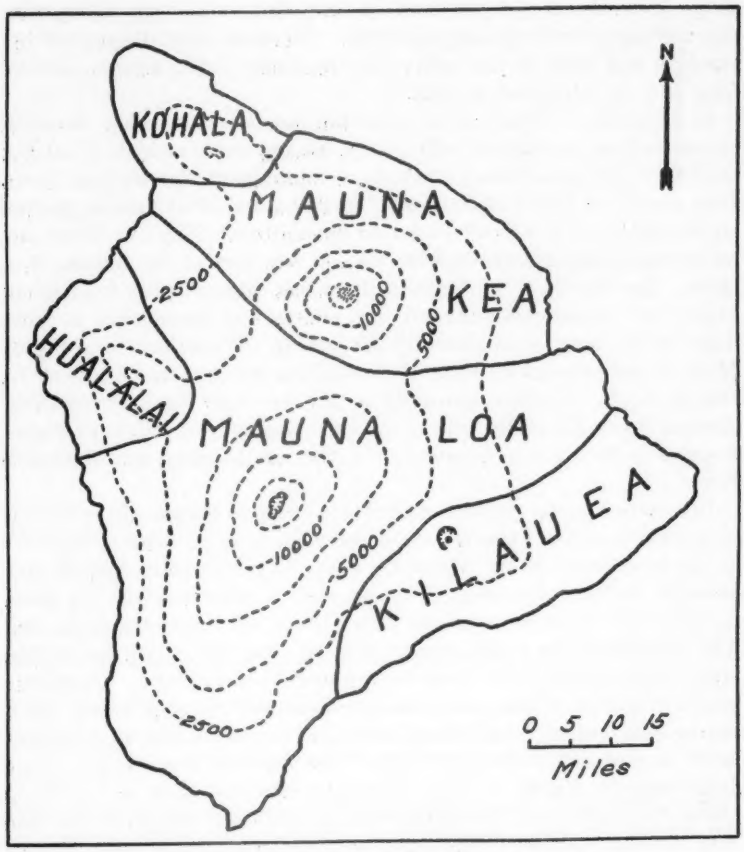

FIGURE 1.—*Sketch map of the island of Hawaii*

Showing outlines of component domes and broad configuration.

more than 80 pyroclastic cones.[14] Puu Makanaka, the largest isolated cone, exceeds 4,000 feet in diameter at the base, 600 feet in height on two opposite sides, and has a nearly circular rim about 1,500 feet in diameter.

[14] As an aid in description, names have been adopted for the following cones not recorded on official maps: Puu Mahoe (Twin Cones), Puu Poepoe (Round Cone), Puu Hoaka (Crescent Cone), Puu Ala (Trail Cone), Puu Waiau (incloses Lake Waiau), Puu Kea (White Cone), Goodrich Cone (Joseph Goodrich, Hawaiian missionary, 1823), Macrae Cone (James Macrae, botanist of the *Blonde*, 1825), Douglas Cone (David Douglas, Hawaiian botanist, 1884), Summit Cone (highest point on Mauna Kea).

DRAINAGE

Only a very rudimentary drainage system is developed on the higher parts of Mauna Kea. So porous is the material of the cinder cones and of the broad sheets of debris between them that water from falling rain and melting snows is quickly absorbed. The cones are little scarred by runways and most of the valleys on the flatter lands assume definite form only in their lower courses.

At 6,500 feet, a circuit of the mountain reveals about eighty channels of intermittent streams, of which only twenty reach as high as 10,000 feet. Only three continuous channels of intermittent streams lead down from elevations above 12,000 feet, Pohakuloa and Waikahalulu gulches on the southwest and Kaula Gulch on the northeast (Fig. 2). There are no perennial streams above 4,500 feet on any part of the Mauna Kea dome. Headwaters of the Wailuku River flow intermittently from about 11,000 feet on the east-southeast side, and several intermittent streams drain to the coast from about 12,000 feet on the northeast and north. Most of these stream channels are ill-defined trenches ranging up to 50 feet in depth. Waikahalulu gulch is 200 feet deep for a considerable distance below the 10,000 foot level, and Pohakuloa is a still more prominent gorge for about 2 miles down the steep southwestern side of Mauna Kea.

In certain respects the most remarkable drainage feature of the Mauna Kea summit area is Lake Waiau—a perennial body of water in the bowl of the comparatively old Waiau ash cone. As measured in August, presumably its low-water stage, it has an area of approximately 1½ acres, a depth of 8 to 15 feet, and lies 6 feet below the lowest sag in its rim. The freshness of its outlet channel suggests that each spring the surplus water from melting snows finds its way to Pohakuloa Gulch. Around the southern half of its shore the beach is moist with seepage water, and a spring hole dug on the southeast side was maintained full to a level of about a foot higher than the lake. The daytime temperature of the lake water in August of three different years was close to 54° F.; in the spring hole about 10 degrees less. At night the margin of the lake was covered with ice. The lake has a yellowish green color derived from organic matter in the water and in the debris which forms its end. Samples of the water and the muck were examined by Lyon with the following result:

"The water from Waiau Lake is a veritable infusion. Bacteria are extremely numerous and probably the chief factor in causing the turbidity of the water. A small ciliate is also present in enormous numbers, while a larger infusorian, *Stylonchia sp.*, is present in large numbers. I also find a few diatoms and numerous dead bodies of a crustacean, *Daphnia sp.* which are being consumed by a fish mold, *Achlya sp.* The sample of muck contains several blue-green algae, desmids, diatoms, at least two species of nematodes, hosts of bacteria and many kinds of protozoa, among which are present all of those found in the sample of water."[15]

[15] Harold L. Lyon's letter to Herbert E. Gregory, dated August 11, 1921.

A chemical analysis of the water made by the Dearborn Chemical Company (December 30, 1929) shows total dissolved solids of 6.424 grains. These include silica, 0.233; iron oxide, .070; calcium carbonate,

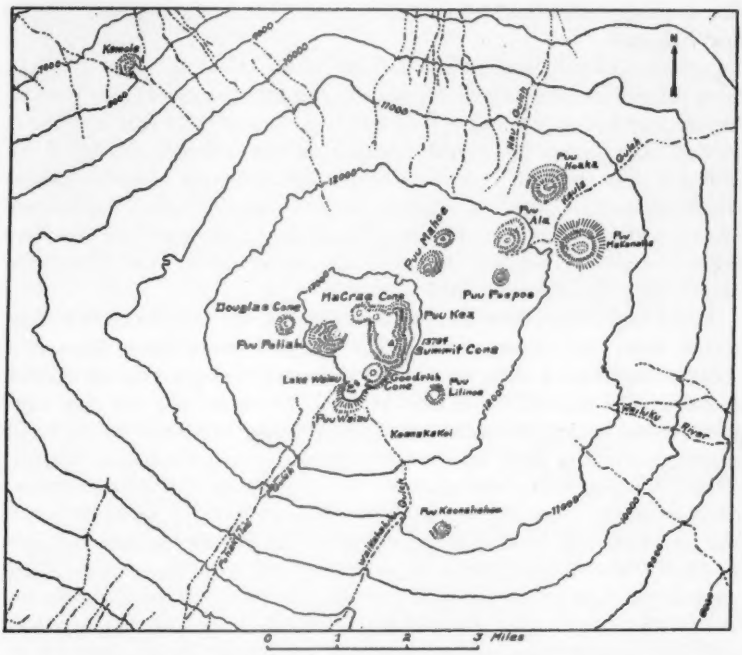

FIGURE 2.—*Sketch map of summit portion of Mauna Kea*

Showing mapped drainage lines and the principal cones. (Data from Mauna Kea and Waikii topographic sheets, United States Geological Survey.)

2.686; magnesium carbonate, 0.789; sodium sulphate, 1.954; sodium chloride, 0.680; sodium nitrate, 0.834. In composition the ratio is much like that from ephemeral Hawaiian streams fed from rain water. As compared with water from the Honolulu artesian basin it is low in silica, sodium, and chlorides and high in iron oxides, aluminum, calcium, carbonates, sulphates, and nitrates.

Lake Waiau is one of the few perennial water bodies in Hawaii. Its position in an area of porous rocks at an altitude of 13,000 feet is worthy of special comment.

CLIMATE

Except for the miscellaneous observations by ranchers and a few instrumental measurements made from time to time by scientists who have

ascended Mauna Kea, knowledge of the climate at the summit platform is based on records made during the years 1895, 1905-1914, at Humuula sheep station and at Lake Waiau during the period August 8-19, 1935. As elaborated by Coulter,[16] these records permit a generalized description of precipitation and temperature characteristic of a subpolar ("tundra") climate.

On the windward (northeast) side of Mauna Kea the zone of maximum rainfall lies between contours 1,800 and 2,000, where annual precipitation may exceed 200 inches. At Humuula (6,685 feet) it is 32 inches, at Puu Kea (8,580 feet) 29.03 inches: at Lake Waiau (13,007 feet) probably less than 15 inches. The rainfall wherever recorded varies widely in amount and distribution—annual, monthly, and daily—and exposure to wind and local topographic features greatly modify the conditions resulting from altitude. On the summit area, precipitation is almost entirely snow and fog.

Above 10,000 feet, snow falls generally during the period October-May and in some years, every month. The repeated snows during the colder seasons may form a thick continuous white cap that remains for several months. The snowfall from most summer storms is light and may rapidly melt. In August, 1926, small snow banks remained in sheltered places; in August, 1935, no snow was found; during a storm in August, 1936, the summit area was covered. During a snow storm in February, 1936, generally regarded as the most severe storm in at least 25 years, the lower limit of snow which remained on the ground around the slopes of Mauna Kea followed approximately the 7,000-foot contour line. Snow to a depth of 2½ feet was reported between Puu Oo and Hookomo on the south slope.[17] Sleet formed part of a brief storm in August, 1935, and several observers report sleet and ice storms during June, July, August, and September.

Fogs are common about the slopes of Mauna Kea especially on the saddle which separates the mountain from Mauna Loa. Humuula during 1895 experienced 177 days of fog. At Laumaia in 1893, 233 foggy days are recorded; "the fogs came during the afternoon" and "remained during the night." On the summit of the mountain, fogs are frequent, at least during the summer season. Those noted at Lake Waiau by the Mauna Kea Expedition came from the west between 11 a.m. and 2 p.m. Other observers report heavy fogs in the late afternoon and at night.

The mean annual temperature at Humuula is 52 degrees: mean maximum, 62.1 degrees: mean minimum, 42 degrees. At Lake Waiau the

[16] C. K. Wentworth, J. W. Coulter, and C. E. Hartt: *The Mauna Kea Expedition of 1935*, B. P. Bishop Mus., manuscript on file.

[17] Letters from E. G. Wingate, William Hartman, L. W. Bryan, and L. R. Smith, all on Hawaii at the time.

FIGURE 1. VIEW SOUTHEAST
Showing contrast between dark slopes of non-glaciated cinder cones and light, surrounding, moraine-strewn glaciated slopes.

FIGURE 2. DETAIL OF SMOOTHED AND STRIATED ROCK SURFACE
Southeast of Waiau Gap.

SCENES NEAR WAIAU GAP

FIGURE 1. CONE 12550
View from the east, showing limits of ice advance marked by block moraine. Note faint line near the top. Original moraine ridge partly overrun by creeping cinders.

FIGURE 2. SUMMIT CLUSTER
View from north slope of Mauna Kea, at about 12,000 feet altitude. Glaciated terrane (foreground), cinder cones (in the distance). Photo by C. J. Kraebel.

CINDER CONES AND SUMMIT CLUSTER OF MAUNA KEA

highest temperature measured during 11 days in August, 1935, was 57.1 degrees, the lowest, 18.9. In January and February, so far as can be deduced from known temperature gradients and airplane observations over Oahu, the general range of mean minima and mean maxima is probably 19 degrees to 41 degrees, with extremes of 10 degrees and 45 degrees, and a mean of perhaps 30 degrees. Freezing temperatures are not uncommon at altitudes as low as 9,000 feet in summer and 6,000 feet in winter. Temperatures above 70 degrees are expected on unclouded days at altitudes below 7,000 feet. At Humuula, the highest temperature recorded is 84 degrees; the lowest, 25 degrees. All observers report that the water in Lake Waiau freezes at night during all seasons of the year. During the summer at least the ice melts during the day. In December 1833, Goodrich found the lake only "about half frozen over".

VEGETATION

Botanically, the alpine zone of Mauna Kea from timberline (9,500 feet) to the summit is a desert, for few species of plants and few individual plants are found. To succeed in the cinders, plants must endure many vicissitudes. Low temperature, short seasons for growth and reproduction, low rainfall, and grazing by sheep and goats combine with high soil porosity and instability of substratum to produce unfavorable conditions. Seeds that drop in the crevices in the lava rocks are the most likely to succeed, and here most of the vegetation is found.

The entire summit area, above 13,000 feet, which bears any vegetation at all is in the pioneer stage. In the alpine zone, 28 species of ferns and flowering plants were found, also several kinds of lichens, a few mosses, algae (in Lake Waiau), and micro-organisms. No plants were abundant; of the xerophytic flora, only one living silversword has been found. The plants found above timberline have been studied by Hartt and Neal, members of the Mauna Kea Expedition.[18]

IGNEOUS ROCKS

The bed rocks exposed on the summit area of Mauna Kea are basaltic lavas and pyroclastics. The lavas are chiefly aa in overlapping flows that range in thickness from 10 feet to as much as 100 feet. In general they seem to be arranged in three groups that have flowed radially outward from the cluster of summit cones to the edge of the summit plateau. One of these groups passes southward down the mountain west of Pohakuloa Gulch, another eastward between Puu Lilinoe and Puu Makanaka, and the third northwestward from saddles east of Puu Paliahu and north of Summit Cone. The lavas are prevailingly fine-

[18] C. E. Hartt and M. C. Neal: *Botanical studies on Mauna Kea.* Paper presented at the Denver session (1937) of the Ecological Society of America. A more comprehensive report is in preparation.

grained, feldspar basalts with numerous coarsely granular inclusions made up chiefly of plagioclase and olivine. The continuity of the surface made of basaltic flows is broken by cinder cones that rise 300 to 800 feet above the nearest exposed lava. These cones are the product of violently explosive eruptions during which masses of liquid were flung into the air by expanding steam and other gases. They consequently consist of small particles of volcanic glass, vesicular cinders of various sizes, and bombs that range in diameter from a few inches to several feet.

The arrangement of the lava flows and cinder cones, their composition, form, and age present many interesting problems not germane to the present discussion.[19]

GLACIATION

EVIDENCES AND EXTENT

The outstanding physiographic feature of the upper slopes of Mauna Kea is an area of fresh, light-colored smoothed bed rock above 12,000 feet, surrounded by weathered rough lava which continues to the base of the mountain. It is a unique feature in the geology of Hawaii not produced by any known process of volcanism or of weathering of igneous rock. These strongly contrasted surfaces have obviously been developed under very different climatic conditions and are of different ages. The surface is like that at the tops of isolated peaks in the Rocky, Sierra Nevada, and Cascade mountains which have been demonstrated to result from long-continued ice-scouring during Pleistocene time. Even in superficial view, glaciation seems a reasonable explanation for the peculiar topography. But, as compared with many other regions, the evidences of glaciation at Mauna Kea are somewhat obscure, and in one-day ascents over established trails, the distinctive proofs may not be recognized. There are no kames or eskers, and in only a few places is a strong marginal moraine developed. Well-defined cirques are absent. Much of the summit area, between cinder cones, is strewn with an ill-assorted rubble of light gray and buff rock fragments. Over large areas this accumulation covers the surface; in other places, elongated ledges of lava are exposed and on them lie a few perched blocks and, at the foot of the high cliffs, a talus of frost-riven fragments.

Closer examination shows that nearly all the rock ledges bear glacial striations on their tops and sides, that the light-colored rubble between the cinder cones is a sparse ground moraine, and that patches of terminal moraine mark the contact of the light-colored, stripped rock and the rough, darker-colored aa. Mapping of the features produced by ice

[19] C. K. Wentworth and A. E. Jones: *Igneous geology of Mauna Kea*, paper in preparation.

scour and ice deposition serves to outline a glaciated area of 27.98 square miles, within which the cinder cones which stood as nunataks occupy 1.97

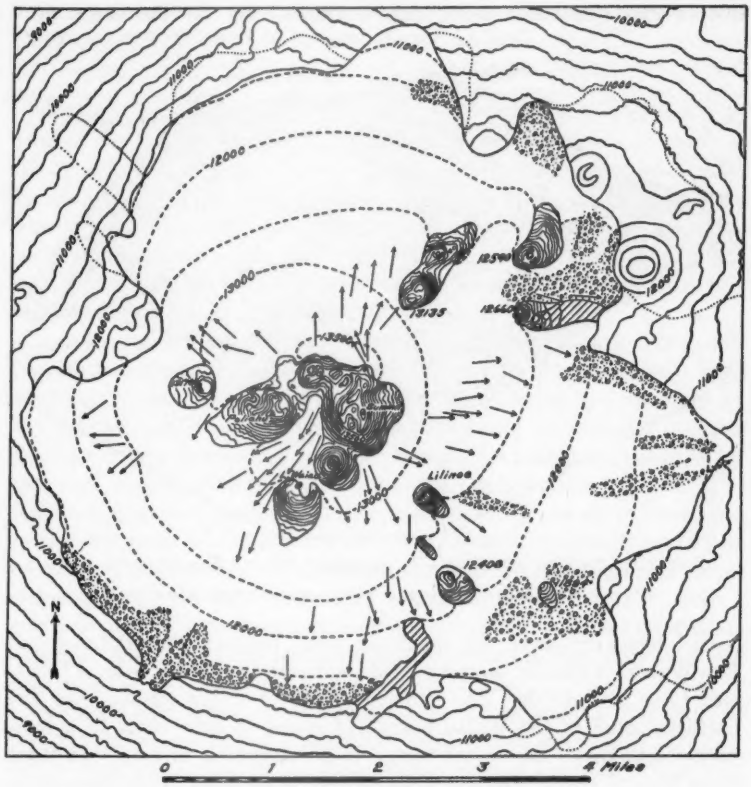

FIGURE 3.—*Map of the glaciated area*

Showing glaciated area (marked by dotted 500-foot contours), cinder-cone nunataks (50-foot contours), observed areas of pronounced morainic cover (stippled) by no means complete, two small postglacial lava flows (cross-hatched), and the directions of glacial striae (arrows). Dotted line outside the continuous glacial margin indicates approximate limit of a supposed earlier glacial advance, so far as observed. The dotted, 500-foot contours are drawn on the restored surface of glacial ice, as determined approximately from ice-limits on cones and the height and distribution of moraines. Supplementary observations, valuable in compiling this map, were contributed by L. R. Smith and A. E. Jones, of the United States Bureau of Chemistry and Soils.

square miles (Fig. 3). The lower edge of the ice lay at altitudes between 10,550 and 12,500 feet. The net area of the ice mass, 26.01 square miles, is less than the present ice cap of Mount Rainier (45 square miles), but

slightly larger and more continuous than the ice on Mount Baker (24.7 square miles).[20]

As shown in Figure 4 the ice moved radially outward from the saddle east of Puu Poliahu in three main channels. By far the larger part

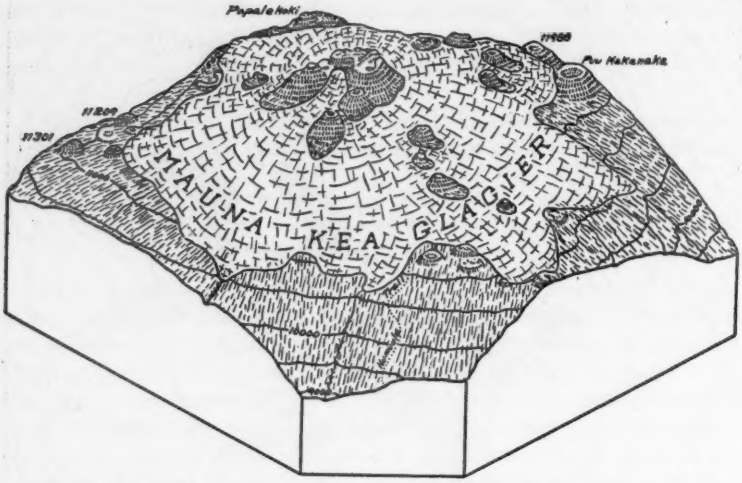

FIGURE 4.—*Probable appearance of ice-capped Mauna Kea from the south*

Isometric block diagram, constructed by isometrograph from contour maps.

passed westward down the mountain slope between Puu Poliahu and Puu Waiau. A smaller tongue moved southeast around the base of Goodrich Cone and divided into two parts, one of which pushed over the northeast bluff of the Waiau basin and seems to have come to a temporary halt inside the crater bowl. It is interesting to note that these three lines of glacial movement correspond in position to the three main series of lava flows.

Field observations show that ice-scouring, though long continued, was comparatively feeble. There is no evidence of deep erosion. The preglacial ledges are smoothed but not destroyed, and rock basins and striated boulders characteristic of intense ice action are conspicuously rare. The morainal material is weathered rock scooped from solid rock beneath. Though talus and slumping of the debris on cinder cones prevents accurate measurements of the volume of glacier ice, striae at different places indicate a thickness of as much as 100 feet. At their source

[20] C. K. Wentworth and D. M. Delo: *Dinwoody glaciers, Wind River Mountains, Wyoming*, Geol. Soc. Am., Bull., vol. 42 (1931) p. 609.

the ice streams were doubtless thicker. The estimated average is 150 feet. If the blocks imbedded in cones were deposited by ice rather than thrown from the craters, the maximum thickness was as much as 350 feet. On the locally steep slopes about the summit, even the minimum thickness was sufficient to initiate glacier motion.

FEATURES OF GLACIAL EROSION

Bands of smooth and striated rock a few feet long and wide are common in the summit area wherever lavas are exposed. Areas as much as 50 by 100 feet in extent, with a nearly continuous pattern of parallel striations, appear in places and give confidence in the recognition of the smaller, more obscurely marked surfaces. Finely graved, or scratched and polished surfaces are the exception. In general, the glaciated surface is smooth and rudely grooved rather than deeply and consistently striated (Pl. 1, fig. 2; Pl. 2, fig. 2).

A conspicuous feature of glacial erosion is the "whale-backed" smoothing (roche moutonnée). Many of the ledges that extend radially down the slope of the dome (Pl. 1, fig. 2) have been eroded and smoothed on the top sides, with a stoss approach upslope and a plucked cliff or series of steps at the downslope end. In general, the roches moutonnées are long and narrow, with parallel sides and a straight rather than oval or domed longitudinal profile. The form of many, if not all of them, has been determined by the original lava flow. Commonly, the irregularities of the lava flow are still in evidence, and in places the deeper pahoehoe wrinkles have not been completely removed. It appears that only a small amount of erosion and smoothing has sufficed to form rather characteristic glacial outlines and surfaces, owing to the similarity in direction of motion of the glacial ice and the lava flows.

Several cinder cones in the summit area, which stood in the path of the moving ice, have been somewhat eroded. This scouring is not generally shown by breaks in the slope profile because the form of the cone is well preserved in the sliding, loose cinders; it is marked rather by a change in color and composition. The original surface layer of red cinders and bombs is replaced by a talus of black cinders derived from layers a few feet below. This color contrast indicates that the cones when formed were mantled with red ejecta, apparently the result of oxidation by the residual heat of the eruption, as also suggested by Dutton.[21] Observation shows that the original red layer is perhaps not more than 10 or 20 feet thick, and that the interior parts of the cone are composed chiefly of dark gray or black cinders which, disturbed by any process, tend to cascade down the slope. On some cones the upper

[21] C. E. Dutton: *Hawaiian volcanoes*, U. S. Geol. Surv., 4th Ann. Rept. (1884) p. 162.

limit of glacial action is shown not only by change in color of the ejecta but also by the emplacement of large light-colored glacial blocks around which the cinders are sliding. Some of the indentations on the sides of cones now covered by talus may represent incipient cirques.

Within the glaciated area, stream channels on rock and presumably also those now buried in debris have broad flat floors and smooth rounded banks. In some the glacial striae on the sides and bottom are well preserved. Near the outer edge of the glaciated area the channels abruptly change into sharply cut gulches or canyons. In Pohakuloa, Waikahalulu, Hanaipoe, and other gulches, post-glacial trenches have been cut in the bottom of the glaciated channel. Pohakuloa Gulch, above 12,000 feet, is a rounded depression with a channel portion not over 25 feet deep, but between 11,000 and 8,300 feet the cross-section, in places, reaches a depth of 150 to 200 feet. Approximately between 12,000 and 11,000 feet post-glacial erosion has cut an inner channel 10 feet deep and locally 20 to 30 feet wide in the rounded, glacially-eroded outer trough. Headward cutting by the Pohakuloa stream, which at times of spring melting must carry considerable volumes of water, has reached to within about 100 feet of the margin of Lake Waiau, and undermined both the heavy lava flows and the ash of Puu Waiau. Blocks of basalt of many tons weight have broken off and tumbled down the steep channel side, probably to be shoved a bit farther by the stream torrent at its occasional maximum.

It seems reasonable to assume that in pre-glacial times the present narrow, straight-sided channels on the slopes of Mauna Kea maintained their characteristic profiles to the summit and, aided by tributaries of similar form, provided means for complete and rapid run-off, in contrast with the present poorly defined drainage system.

FEATURES OF DEPOSITION

A thin and discontinuous ground moraine overlies striated bed rock in much of the glaciated area (Pl. 1, fig. 2). It consists of fragments of lava, in many places mingled with cinders from nearby cones or with finer rock detritus washed from the slopes. Nearly all the fragments are angular or slightly rounded at their edges, though a few are marked by minor grooves and facets and generally granular surfaces. It seems obvious that the "erratics" have not traveled far or been subjected to intense and repeated grinding. Some of them are joint blocks plucked from the underlying ledge; others are slabs broken from low cliffs over which the ice stream passed; still others seem to have been transported within, or on top of, the glaciers, without modification in shape. There is a conspicuous absence of the finely rounded and highly polished boulders common to Pleistocene drift of other regions, and no glacial "rock

flour" consolidated into boulder clay was observed. Though much of the bed rock is vesicular or granular and thus less suitable than quartzite or dense limestone for fine graving and polishing, fragments from the compact diabases if overturned, ground, and reground by thick moving ice would have lost their original forms.

Much of the material transported by Mauna Kea glaciers is deposited as lateral and terminal moraines (Pl. 3). Because the ice mass was continuous over the summit area and developed separate tongues only at its outer edge, long lateral moraines characteristic of valley glaciers were not developed. In a few places, the two types of moraines are readily distinguishable, but, in general, they are bunched in the zone that marks the contact of glaciated and unglaciated terraines. As shown in Figure 3 the combined moraines, so far as observed, form a broken collar at an average altitude of 11,250 feet. To determine accurately the relation of the moraines to parts of the ice mass, their extent, composition, and distribution, involves more detailed mapping than has heretofore been possible.

A preliminary study was made of the prominent moraines at Puu Ala and in Pohakuloa Gulch. At Puu Ala, a lateral moraine extends as a ridge more than half a mile long, a quarter of a mile wide, from the base of the cone northeastward to the flanks of Puu Makanaka. The glacial debris of which it is composed, 100 to 150 feet thick, was deposited by an ice tongue that passed between Puu Ala and Puu Poepoe. On both sides of Pohakuloa Gulch, a conspicuous cover of glacial debris, including large blocks, extends down the valley for nearly half a mile from an altitude of about 11,250 feet to a lower limit of about 10,500 feet. Adjacent to the upper parts of these tongues of debris, and extending laterally each way along the contour of the mountain, is a marginal moraine especially prominent on its steep, downhill slope. In places, the deposit is 150 feet or more in thickness. Sheets of debris on the sides of the gulch represent the lateral moraines of the Pohakuloa ice tongue which probably advanced beyond the general position of the terminal moraine, owing to its greater depth and velocity of movement. The relationship of the marginal moraine to the dome of Mauna Kea is clearly seen when looking upstream from the flats near the Pohakuloa Camp (altitude 6,500 feet), especially at sunrise or sunset when the glacial pile is brought into sharp relief in the oblique lighting (Pl. 4, fig. 1).

Out-wash gravels and sand deposited when water from the melting glacier greatly augmented the normal run-off are distributed along many valleys. Most of the material lies just inside or just outside of the limits of glaciation. In the larger valleys, it extends downstream for a mile or more. The material consists of poorly assorted and little-

rounded fragments much like that in the moraines. Within the channel and on the adjoining floodplains of Pohakuloa Gulch, between contour lines 8,000 and 6,500, the outwash is particularly extensive, and includes boulders several feet in diameter.

Two epochs of glaciation are suggested by the arrangement and composition of the outwash on the east side of Pohakuloa Gulch at altitudes between 8,000 and 9,500 feet. Below the terminal moraine in this region, a sheet of gravel and boulders, apparently derived from a relatively recent lava flow, extends some distance downstream. It is conspicuous in a strip a few hundred yards wide along the side of the gulch. The edge of this strip of coarse outwash is slightly frayed and reveals, here and there, an underlying formation of different texture which is also exposed in the wall of the gulch. This older outwash includes cobbles and boulders that resemble those of the overlying formation, and also a few boulders that clearly show striation, and others that undoubtedly are of glacial origin. Boulders derived from the recent basalt flow seem to be absent. But, unlike the loosely piled material spread over the surface, the underlying deposit is firmly cemented into a conglomerate. Furthermore, the matrix is almost wholly composed of volcanic ash, indurated into a gray tuff. It is probable that the tuffaceous matrix played some part in the induration of parts of the great outwash fan adjacent to Pohakuloa Gulch channel below an altitude of 8,000 feet, but no detailed comparative studies or measurements of sections were practicable in the time available.

BASIN OF LAKE WAIAU

Lake Waiau lies in the bowl of Puu Waiau—a cone built chiefly of fine-grained and much-weathered cinders and ash. On its north side, the cone is breached and thus forms an outlet for the lake at high water stages. As the average depth of the lake when full of water is about 15 feet and the muck at its bottom as much as 8 feet, the floor of its basin lies 23 feet below the lowest part of its rim. In superficial view, Waiau has the appearance of an ordinary crater lake, but striae directed toward the basin from the northeast, morainal deposits high up on its southern slope, and scour marks on its outlet bar, show that it was occupied by glacial ice. It seems probable that ice to a depth of 100 feet or more was forced into the basin and after a temporary halt was forced out to join the larger ice tongues moving down Pohakuloa Gulch. Scouring by the ice doubtless deepened the original basin, and it may be that some ice remained after the glaciers disappeared. The possibility is suggested that downward seepage of lake water is impeded not only by fine-grained ash and organic material but also by ground ice that probably forms each year.

FIGURE 1. TERMINAL MORAINE AT 10,500 FEET ALTITUDE
On the two sides of Pohakuloa Gulch, as seen from the Humuula road, near the C.C.C. camp at Pohakuloa.

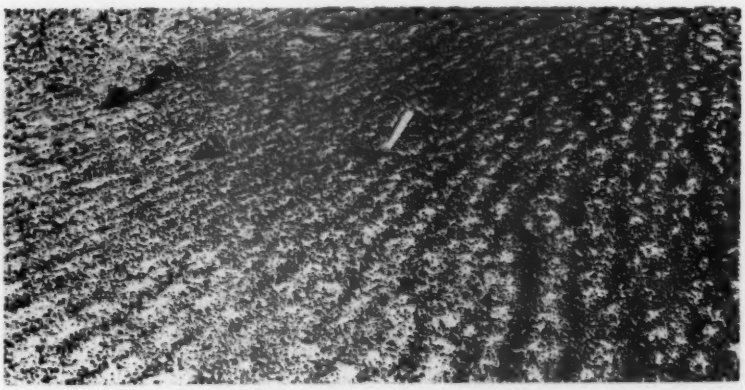

FIGURE 2. DETAIL OF ROCK STRIPES OR HACHURED GROUND
Photo by L. R. Smith.

TERMINAL MORAINE AND ROCK STRIPES

FIGURE 1. EDGEWISE PACKING OF FROST-FLAKED ROCK CHIPS
Detail showing rude polygonal pattern made by ground freezing. Area shown is about 2 feet wide.

FIGURE 2. RELATION BETWEEN OUTWASH GRAVELS AND LAVA-FLOW VENEERS
Diagrammatic section showing area on southwest slope, east of Pohakuloa Gulch.

WORK OF SNOW AND ICE

Though the cone-dotted summit plateau of Mauna Kea lacks the ruggedness of most high mountains, the generally smoothed surface produced by glaciation has been much modified by the work of snow and ice.

Around the margins of cinder cones a thin layer of cinders had crept outward and downward into a zone evidently once covered by glacial ice. In places, the cinders surround and nearly cover large glacial blocks which remained in place while the finer material crept downward under snow banks. Here and there, long trains of stones extend down the slopes. They are conspicuous at about 13,000 feet altitude north of the summit cluster of cones. These so-called "rock glaciers" are probably due to a slow, downhill creeping aided by freezing and thawing, though some of the blocks may have slid to their present position on the solid crust of snow banks. Not uncommonly, low marginal wrinkles lie parallel to the edge of the creeping cinders. In some places the exposure of black cinders by displacement or removal of the superficial red cinders is a feature of nivation rather than of erosion by glacial ice.

Another feature associated with nivation and frost work is the conspicuous "striped ground" or "hachured ground" observed in many places and particularly well developed on the non-glaciated lower slopes of cinder cones (Pl. 4, fig. 2). The stripes are slightly raised ridges of coarser fragments, with intervening shallow furrows of finer material. The size of the particles varies according to the texture of the original surface material. In general the coarser fragments are about a centimeter in diameter; the finer, the size of large sand grains and smaller. The stripes are developed on surfaces with slopes of 3 or 4 degrees to 20 degrees and trend directly down the steepest slope, producing the appearance of hachures laid out on the ground. Spacing between stripes also varies according to the texture of the material. Where the coarser particles measure as much as two centimeters, the spacing is about 5 or 6 inches; where 5 millimeters, the interval is about 1½ inches. These stripes are believed to be due to frost heaving and sorting of rock debris in the surficial layers, and are evidently related to the "stone nets" or polygonboden developed in many regions where frost heaving is relatively active and other processes locally feeble.[22]

On Mauna Kea, polygonboden are imperfectly developed. In small areas of playa, filled mostly with fine-grained mud and silt, there are

[22] Ernst Antevs: *Alpine zone of Mt. Washington Range* (1932).
Thomas Hay: *Stone Stripes*, Geog. Jour., vol. 87 (1936) p. 47-50.
Robert L. Nichols and Frances Nichols: *Polygonboden on Mt. Desert Island*, Maine Science, n. s., vol. 33 (1936) p. 161.
Hans Steche: *Beitrage zur Frage der Strukturboden*, Sachsisch. Akad. Wiss., Math-Phys. Klasse, Bd. 85 (1933) p. 193-272. This is a world-wide summary with cited observations from 1815.

faint polygonal patterns in which the sides of polygons about 6 inches across are formed of small rock fragments crudely stacked on edge, and surrounding centers of sand and mud. In another type the pattern is formed of edgewise-stacked, frost-split spalls, 2 to 3 inches across, and ¼ to ½ inch thick, that form polygons about a foot across. On some of the steeper slopes where the creep is more active, the polygons are arranged in parallel rows of edgewise stacked spalls which extend down the slope, with intervening zones of spalls lying flat. The sizes of the edgewise and flatwise spalls is about the same (Pl. 5, fig. 1). In forming this type of polygonboden, no fine-grained mud or silt is involved; the whole surface consists of flake-like spalls. In places, elongated polygonboden have forms intermediate between the parallel rows on the slopes and the nearly symmetrical polygons of flat surfaces. In the shallow bowl of Douglas Cone, frost spalls ½ to 6 inches are rather crudely arranged in edgewise configuration around the sides of polygons 3 to 4 feet in diameter. Within the polygons is finer rubble, but no real clay or silt.

These limited observations strongly suggest that rock stripes and polygonboden are related. In places there is a definite transition downslope, from one pattern to the other. It is generally agreed that these striped and polygonal ground forms are due to freezing and thawing of the surface layers, with consequent creep and re-arrangement of the coarser and finer material, but the exact mechanism is not yet well understood.[23] The patterns are characteristic of high latitudes and high altitudes where soil and fine rock materials of fairly uniform constitution are subjected to freezing through much of the year and where other processes of weathering are relatively feeble.

Over the glaciated area of Mauna Kea the wedge-work of ice is conspicuous. The bed rock has been shattered, and spalls and slabs by thousands are strewn over the surface. In addition to the little-weathered, light gray fragments transported by glacial ice, large quantities of broken rock talus lie at the bases of cliff ledges, and, in many places stand in great stacks of flat or curved slabs only little removed from the bedrock itself. Some of the frost blocks are chunky or roughly columnar in form. Especially at the sides and downslope ends of thick lava flow or tube masses, the rock has spalled off in straight or slightly curved slabs, one to several inches thick and several square feet in area.

Not only are the ledges frost-riven, but many blocks of basalt in the ground moraine and in the talus of cones, some of them only a few inches in diameter, have been split neatly into slices which lie stacked near

[23] Otto Nordenskjold: *The geography of the Polar Regions*, Am. Geog. Soc. (1928) p. 53-56.
E. de K. Leffingwell: *The Canning River Region*, U. S. Geol. Surv., Prof. Paper 109 (1919) p. 210.

their place of origin. In some such rocks an original or developed fissile structure permitted easy splitting, but joint cracks and incipient fissures produced by moving glacial ice seem to have afforded the most suitable conditions. In general, the shapes and sizes of spalls appear to be due largely to the structures developed in the lava flows during cooling (Pl. 5, fig. 2). The present climate of the mountain summit is favorable for frost work, and probably has been favorable for frost work during all post-glacial time. The temperature falls below the freezing point every night in the year, and, with the possible exception of short periods during the winter, it rises above freezing point each day. Thus alternate melting and freezing of ice in cracks is nearly a continuous process. Moreover, daytime melting of the snow banks that during most of the year lie in sheltered places permits water to trickle down rock surfaces and into all accessible crevices, only to be frozen at night. Observations indicate that the wedgework of ice on Mauna Kea is an exceptionally active process, perhaps ten times more effective than in most parts of the northern United States.

REGIONAL RELATIONS

The glaciers on Mauna Kea are the local expression of the world-wide lowering of temperature during the ice age which resulted in the accumulation of ice a few hundred to several thousand feet thick over an area of more than 6,000,000 square miles of mountain and lowland. Conditioned by this decrease in temperature, the snow fields were greatly expanded and reached much lower altitudes. In many regions, perpetual snow and unmistakable features of glaciation make it possible to mark the position of the lower limit of Pleistocene snow and ice. Thus in the latitude of Hawaii, the snow line in the Andes, now at 15,000 to 19,000 feet stood 3,000 to 4,000 feet lower. On Mauna Kea, where a perpetual snow cap is lacking, the altitude of the ancient snow line can only be estimated. It seems probable, however, that the shift on mountains in mid-ocean would be less than on continental areas. As the glaciated area extends from the summit to an average of 11,250 feet, and a considerable area of persistent snow is required to maintain ice movement, the summer snow line of Pleistocene time probably was not far from 12,000 feet and the winter line considerably lower. It is estimated that if the mountain were sufficiently high, the present snow line of Mauna Kea would stand at about 15,000.

The world-wide decrease of land temperatures during the Pleistocene period was accompanied by lowered temperature of sea water which, in time, brought a changed environment for the fauna and flora. Doubtless also, the environment was further modified by a re-alinement of

winds and currents incident to shift in zones of temperature and increase in amount of snow. During glaciation, plants that may have grown about the summit of Mauna Kea were destroyed, and no buried remains have been found. Doubtless some species retreated downslope and returned to constitute the present sparse vegetations of lichens, a few mosses, a fern, and eleven species of flowering plants. Because of this isolation from continental areas, migrating plants of alpine and arctic types may not have reached the mountains since the ice disappeared.

For marine organisms, whose distribution and rate of growth is influenced by even slight changes in temperature and composition of sea water, the glacial climate was of profound significance. In particular, the shift from warm to cool climate and back again to warm climate is recorded by the plants and animals that constitute the coral reefs. In Hawaii the minimum temperature of sea water is 23° C, only 3 degrees above the lowest limit at which corals grow. During the Pleistocene various lines of evidence show it to have been 3 to 10 degrees lower. In waters at these temperatures, corals could not thrive, and, lacking the defensive cover of organic life, reefs that may have been present in preglacial time would have been destroyed by the battering surf. It therefore seems highly probable that while the summit of Mauna Kea was capped with ice the waters about its base held no reef-building organisms. Even today the Hawaiian reefs are small and discontinuous and their growth is not vigorous. Vaughan [24] has shown that their fauna is Indo-Pacific, transported by east-moving currents, and doubts that any of the species are peculiar to Hawaii. The known rate of coral growth shows that post-glacial time is ample for the building of Hawaiian reefs, and also the much greater barriers and fringing reefs about tropical Pacific islands.

While Pleistocene climates prevailed, the earth was not only chilled; the relation of sea to land was also affected. During the successive glaciations that increased the amount of polar ice and expanded the continental and mountain glaciers, much water must have been taken from the oceans, resulting in a lowered sea level. Daly [25] estimates that the water locked up as ice during the Pleistocene is sufficient to have lowered the surface of the oceans approximately 90 meters. In other words, since Mauna Kea was capped with ice, the sea level of Hawaii has risen about 300 feet. It is further estimated that if all the existing ice masses were melted the surface of the oceans would stand about 165 feet still higher. Changes of sea level that plausibly may be attributed to increase and decrease of glacial ice are shown by wave-cut benches below and above

[24] T. W. Vaughan: *Recent Madreporia of the Hawaiian islands and Laysan*, U. S. Nat. Mus., Bull. 59 (1907).

[25] R. A. Daly: *Changing World of the Ice Age* (1934) p. 12, 46-48.

present sea level. A bench standing 12 to 20 feet above sea level has been observed in many widely separated places, and is well developed in Hawaii and other Pacific islands. Less prominent features on Maui and Oahu have also been correlated with glacial and inter-glacial stages.[26]

The last expansion of glacial ice, and probably the earliest expansion, post-dated most of the volcanism that gave Mauna Kea its present form.

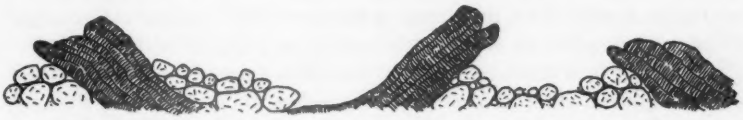

FIGURE 5.—*Relation between outwash gravels and lava-flow veneers*
Diagrammatic section showing area on southwest slope, east of Pohakuloa Gulch.

Several of the cones have been scoured by ice which passed their bases, and the freedom of the summit area from cinders and ash, except at the immediate slopes of cones, indicates that no explosive eruptions from a major vent have taken place in post-glacial time. However, a few features indicate that some volcanic activity continued into glacial time, and that a few minor eruptions may have occurred since the recession of the ice.

On the southwest slope east of Pohakuloa Gulch, slightly above the 10,000-foot level (Fig. 5), elongated, monoclinal masses of basalt, 5 to 15 feet thick and dipping 20 to 50 degrees laterally, trend down the main slope of the Mauna Kea dome for several hundred feet. In places, two masses run parallel, dipping toward each other. Under the overhanging side of some of these inclined lava masses are remnants of a gravel formation, and near others a coarse outwash gravel overlaps the upper side, or gravel is in contact on both sides. It is fairly clear that these lavas were formed by post-glacial or interglacial eruptions and flowed down the channeled surfaces of the outwash-gravel fans, in markedly linear courses. Probably, because of the steep slopes and the pre-formed channels, the flow was rapid and the channels were filled to the brim but did not remain full as the flow declined. Apparently no complete lava filling cooled, but, instead, channels were floored and walled with these chilled linings, conforming to the wetted perimeter. Perhaps in places, events were recurrent. At any rate it appears that both pre-volcanic and post-volcanic outwash gravels were deposited: the remnants of the partially

[26] R. A. Daly: *The glacial control theory of coral reefs*, Am. Acad. Arts, Pr., vol. 51 (1915) p. 157-251; Geol. Mag., vol. 57 (1920) p. 346; *Changing World of the Ice Age* (1934) p. 157-164 (a summary).

C. K. Wentworth and H. S. Palmer: *Eustatic bench on islands of the north Pacific*, Geol. Soc. Am., Bull., vol. 36 (1925) p. 521-544.

H. T. Stearns: *Pleistocene shore lines on Oahu and Maui*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 1950-1953.

exposed laterally dipping lava flows are now found in a variety of relations to them.

In several places west and northwest of the Puu Keonehehee, aa flows overlap the glacial moraine lying along the east side of Waikahalulu Gulch. These flow lavas appear to have come from the small cone just northwest of Keonehehee (12,000 feet altitude). Near the base of Keonehehee, coarse pyroclastics and large bombs showing little or no erosion appear to overlie morainic material, but it is thought that this material may have worked down the slopes of the cone. With present information a date of formation of Keonehehee cannot be assigned with confidence. Certainly the lava flow and probably the entire mass of the adjacent cone are post-glacial. Another post-glacial lava flow apparently from the east base of Puu Poepoe extends about ¾ of a mile east to the 12,000-foot contour line, south-southwest of Puu Makahaka. Around its margins this flow overlies glacial gravels and its tip appears to cross the terminal moraine. Puu Poepoe, from the base of which this flow comes, however, seems to be older at least than the last glacial advance; it stood as a nunatak while a pronounced ice tongue passed between it and Puu Ala.

As the markings on large flows and cones show that glacial ice moved over a terrane having substantially the same configuration as now, and the clearly post-glacial flows are few and small in the immediate summit area, it is certain that all the large cones and the mountain as a whole assumed their present forms in pre-glacial time. Features that indicate eruptions during some specified inter-glacial epoch have not been observed and would perhaps be difficult to find. If an explosive eruption should take place through a glaciated terrane any striated rocks disturbed would probably be deeply buried by pyroclastic material before the eruption ceased. Around its margin the cone would overlap glaciated ledges, but, in present exposures, the material that might thus be newly deposited is impossible to distinguish from that due to gravity or solifluction slumping.

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SILURIAN STRATA OF NOTRE DAME BAY AND EXPLOITS VALLEY, NEWFOUNDLAND

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INTRODUCTION

The occurrence of Silurian strata in White and Notre Dame bays and the Exploits Valley has been known since the explorations of Murray and Howley more than sixty years ago. These explorations, reconnaissance in nature, yielded little information concerning thicknesses, lithological characters, and faunal contents of the sedimentary rocks. The few Silurian fossils reported were of such general or uncertain identification as to have little value for precise age determination and specific correlation. It was not until 1910, when Charles Schuchert examined the collections of the Geological Survey of Newfoundland at St. John's, that the fossils were more definitely identified and the stratigraphic position of the fossiliferous Silurian strata of Newfoundland was somewhat more exactly determined.

Since the Silurian strata of northern Newfoundland are the most eastern known on the North American continent, the contained fossils are of paramount importance for correlation with the European Silurian. The meager information available in 1935 precluded determination of the exact position of the Newfoundland strata in the Silurian system; did not show whether the Silurian faunas of Newfoundland were related to those of Anticosti, as seemed probable, or to those of the Acadian geosyncline as developed at Arisaig, Nova Scotia; and failed to demonstrate whether the sediments had been deposited in the Appalachian or the Acadian geosyncline.

The need for more definite information concerning the Silurian of Newfoundland became apparent in 1934 when the senior writer began the preparation of a contribution on the Silurian strata of the St. Lawrence region for a projected memoir on the stratigraphy of North America. As a step toward acquiring additional information, the writers requested a grant from the Grants-in-Aid Committee of the United States National Research Council. This request was approved, and the grant made possible the field work done in the summer of 1935 along the coast and on the islands of Notre Dame Bay and along the Exploits River. The writers were assisted in the field by W. S. Twenhofel, son of the senior writer, and by Adam Peckford, owner and operator of the motor boat used during much of the work.

Unfortunately, one of the most important exposures was not seen in 1935 because there are two islands in Notre Dame Bay bearing the name of Yellow Fox, and the strata of the wrong one were studied. Another important exposure was not seen because its existence was then unknown to the writers. This had been discovered by George R. Heyl, in the midst of a flow breccia on Upper Black Island in the Exploits Estuary. The region of White Bay was not visited at the time because a party

of the Geological Survey of Newfoundland was working in that area, and it did not seem wise to duplicate effort. Subsequently, A. K. Snelgrove, Director of the Geological Survey of Newfoundland, expressed the wish that the strata of White Bay be examined, and this led to the senior writer's again visiting the island in the summer of 1936. This later work, partly supported by the Geological Survey of Newfoundland, included a study of the strata in Notre Dame Bay not seen in 1935, a re-study of some of the sections seen that year, and a brief examination of the Silurian strata of the White Bay region which were then being studied by Heyl.

The Silurian fossils collected at various times by Snelgrove and his associates were given to the writers for study, and they take this opportunity of expressing their gratitude for the courtesy. These fossils will be described in another paper.

PREVIOUS INVESTIGATIONS

The earliest published studies of the Silurian of Newfoundland were made by Murray and Howley.[1] In 1864, Murray studied the geology of the eastern coast of the great northern peninsula and parts of the coasts of White, Hall, and Notre Dame bays.

The strata of Exploits Valley and Notre Dame Bay were investigated by Murray and Howley in 1871. Murray gave most of his attention to the former, whereas Howley studied the rocks along the coasts and on the islands of Exploits and Notre Dame bays. The strata assigned by these authors to the Silurian were discussed under the heading, "Upper Formations, Trap Dykes and Overflows." They commented briefly concerning the distribution and nature of the rocks but gave little detailed information. Fossils collected by them in Goldson Arm, New World Island, were identified by Billings as "*Favosites Gothlandicus, Heliolites?, Zaphrentis bellistriata,* an encrinite referred to the genus *Glyptocrinus,* a coral referred to the genus *Heliophyllum, Orthis ruida, Leptaena sericea,* or perhaps *transversalis,* ventral valve of an orthis like *O. Davidsoni, Strophomena rhomboidalis, Atrypa reticularis, Stricklandinia lens, Modiolopsis, Ambonychia,* a trilobite, genus *Encrinurus;* and some others not determinable."[2] A few fossils were reported from other localities. This list of fossils proves the Silurian age of the fossiliferous strata but does not permit a more specific correlation.

[1] A. Murray: *Report . . . for 1864, upon the geology of the eastern coast of the Great Northern Peninsula, and portions of Hall's Bay, Notre Dame Bay, and White Bay* (1865) p. 4-50. Republished in *Geological Survey of Newfoundland* (1881) p. 4-50. London.

A. Murray and J. P. Howley: *Report for 1872,* Geol. Surv. Newfoundland (1872) p. 250-278. Republished in *Geological Survey of Newfoundland* (1881) p. 250-278. London.

[2] A. Murray and J. P. Howley: *op. cit.,* p. 270.

Excepting general statements in connection with other subjects, nothing additional concerning the Silurian of Newfoundland appeared until Sampson [3] published an article on the ferruginous cherts of Notre Dame Bay, in which he stated that the "Silurian rocks [of Notre Dame Bay] are principally red sandstones and conglomerates, usually red. Very thick sections are exposed, those being in the extreme south of the bay and on the Exploits River. They are in places highly fossiliferous. Volcanic rocks are almost entirely absent in the known Silurian. No chert has been found in the Silurian."

In 1928, Snelgrove [4] published a report on the geology of the central mineral belt of Newfoundland, in which he quoted Sampson with respect to the Silurian strata.

Schuchert and Dunbar [5] listed the fossils from Herring Neck identified by Schuchert in 1910, when he studied the collections of the Geological Survey of Newfoundland. The list includes the following:

Favosites gothlandicus
Heliolites sp. Corallites about 3 mm. in diameter.
Zaphrentis bellistriata
Atrypa marginalis
Dalmanella elegantula
Leptaena rhomboidalis
Orthis near *O. davidsoni*
O. sp., similar to *O. maria* of Anticosti.
Schuchertella sp., near *S. pecten*, but with the striae in bundles.
Sowerbyella sp., more like *S. sericea* than *S. transversalis.*
Stricklandinia lens
Ambonychia? sp., smooth forms like those of Jupiter River, Anticosti.
Acaste sp.
Encrinurus sp.

From Goldson Arm of the same general locality, they listed the following:

Dalmanella elegantula
Leptaena rhomboidalis
Sowerbyella sericea? Not *S. transversalis.*
Stricklandinia n. sp. A very wide trilobed shell.
Bronteus sp.
Encrinurus sp.

Recent work on the Silurian and associated geology of Newfoundland has been carried on by A. K. Snelgrove. In a recent paper, he [6] referred to the fossils reported by Murray from Sops Arm and indicated the fossiliferous strata (Cambrian to Devonian?). The most recent paper mentioning the Silurian of Newfoundland is that of Heyl,[7] who, in de-

[3] E. Sampson: *The ferruginous chert formations of Notre Dame Bay, Newfoundland,* Jour. Geol., vol. 31 (1923) p. 571-598.

[4] A. K. Snelgrove: *The geology of the central mineral belt of Newfoundland,* Canad. Min. Met., Trs., Bull. 197 (1928) p. 1057-1127.

[5] Charles Schuchert and C. O. Dunbar: *Stratigraphy of Western Newfoundland,* Geol. Soc. Am., Mem. 1 (1934) p. 103.

[6] A. K. Snelgrove: *Geology of the gold deposits of Newfoundland,* Newfoundland Dept. Nat. Res., Geol. Sec., Bull. 2 (1935) p. 38, map facing p. 38.

[7] G. R. Heyl: *Geology and mineral deposits of the Bay of Exploits area,* Newfoundland Dept. Nat. Res., Geol. Sec., Bull. 3 (1936).

scribing the geology and mineral deposits of the Bay of Exploits area, referred briefly to the Silurian.

The present paper discusses the Silurian strata of Notre Dame Bay and the valley of the Exploits River; Heyl in a later paper will consider the Silurian of the White Bay region.

OUTLINE OF SILURIAN GEOLOGY

REGIONAL DISTRIBUTION

So far as known, definitely identified Silurian strata occur in two general localities in northern Newfoundland: one, a large area lying between, and to some extent on both sides of, the Exploits and Gander rivers and extending from the central part of the island northeastward to the coast of Notre Dame Bay, and thence seaward on the islands offshore; the other, an area along the west side of White Bay in the northwestern part of the island (Fig. 1). Exposures are numerous and many of them are extensive along the coasts of the mainland and on some islands in Notre Dame Bay, but are few and restricted in the interior.

REGIONAL STRUCTURE

The Silurian and contiguous strata of the area around Notre Dame Bay and along the Exploits River are fairly closely folded into northeastward-trending, asymmetrical anticlines and synclines which, in numerous instances, have been overturned toward the northwest and thrust-faulted along southeastward-dipping fault planes that parallel the regional trends of the folds. The axial planes of the folds dip southeastward and the folds pitch to the northeastward or to the southwestward. The strata in general stand at high angles, many are vertical, and in some instances appear to be overturned. In addition to the major thrust faults, there is a complex system of normal or gravity faults. The faults seem to be contemporaneous with, or subsequent to, the folding. It is hardly necessary, therefore, to emphasize that any sections of strata, other than those obviously continuous, may have parts missing or duplicated.

The coastal physiography strongly reflects the regional structure as shown in the alignment of the coastal indentations, headlands, tickles, and islands which are usually elongated in harmony with the structural trends.

METAMORPHISM

Nearly all the Silurian strata are more or less metamorphosed, and on Yellow Fox Island the alteration has been intense. At some localities, however, as in Goldson and Pike arms on New World Island, on Change Island, along the west shore of Exploits Estuary between Wigwam Point and Botwood (Fig. 2), and along the Exploits River at Grand Falls and

Bishop Falls, the strata have not been so strongly affected except immediately adjacent to intrusive masses of igneous rock. Where strata, presumably Ordovician in age, have been seen in contact (fault contact only) with Silurian rocks, the former seem to be the more altered, thus

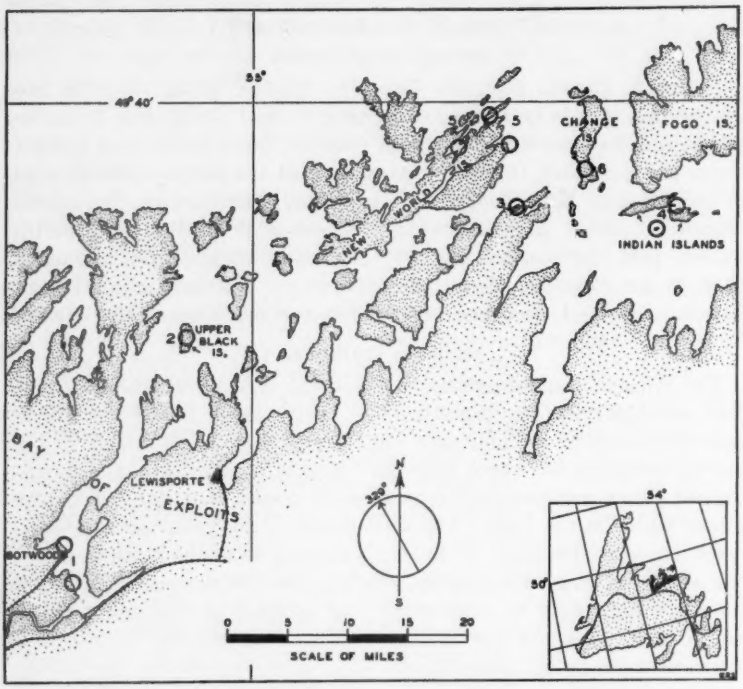

FIGURE 1.—*Map of a portion of Notre Dame Bay and the Bay of Exploits*

Showing nature of coast and location of sections described: (1) Botwood; (2) Upper Black Island; (3) Port Albert (Ordovician); (4) Indian islands and Yellow Fox Island; (5) Goldson and Pike arms and Long Tickle; and (6) Change Island. Small insert map shows Notre Dame Bay area. Map based on United States Hydrographic Office Chart No. 1101 (1923).

suggesting the possibility that some deformative movement may have taken place in some parts of the region after deposition of the Ordovician sediments, but before the laying down of Silurian sediments. It should be emphasized, however, that in such situations, Ordovician slates were compared with Silurian sandstones or quartzites. The apparent difference in alteration might disappear if similar lithologies of the two systems could be compared in the same locality.

STRATIGRAPHY

The sequence of strata exposed in the Notre Dame Bay region seems to comprise an apparently continuous and conformable succession, of which the upper part is known to be Silurian and the lower part, Ordovician. The apparent thickness of the sequence, which is of the order of magnitude of 10,000 to 15,000 feet, may be increased or decreased in the future by the discovery of faults duplicating or concealing parts of the succession.

The exact nature of the stratigraphic contact between the Ordovician and the Silurian strata in the region of Notre Dame Bay is unknown, as the strata of the two systems have not been seen in actual contact except along faults. If the Silurian sequence has been interpreted correctly, it consists in descending order of (1) dark-gray to black shales and red sandstones, (2) thick- and heavy-bedded conglomerates, and (3) fairly thin-bedded, red sandstones, of which all are more or less altered to the respective metamorphic equivalents. In order of thickness and areal extent, the sandstones (quartzites) constitute the largest portion of the Silurian succession and are the most widely distributed. They are well exposed along the western shore of Exploits Estuary (Fig. 2) south of Botwood, along the coast of Change Island, and along Exploits River at Bishop Falls and Grand Falls. These sandstones are here named the Botwood formation, with the type section comprising the exposures between Peter Arm and Wigwam Point (Fig. 2).

Second in importance are the conglomerates (conglomerites), the most spectacular of the lithologic units in the succession because of unusual thickness (1,000 feet or more), extensive distribution, lithologic characteristics, and resistance to erosion. The last-named characteristic is responsible for the bold headlands and narrow ridges which are conspicuous wherever the conglomerate is exposed. This conglomeratic unit is here designated the Goldson formation, from its extensive exposures along the southeastern shore of Goldson Arm where it contains Silurian fossils (Fig. 4).

The shales (argillites [8]) and sandstones (quartzites), which appear to constitute the upper portion of the Silurian sequence, are fossiliferous and are well exposed in Goldson and Pike arms of New World Island, and on Yellow Fox Island just south of the Indian Islands. These strata are here designated the Pike Arm formation, from the excellent exposures on "Fossil Point" in Pike Arm (Fig. 4).

The stratigraphic position of the fossiliferous limestones found in the flow breccias on Upper Black Island (Fig. 1) is unknown, except that

[8] The term argillite as used in this paper refers to argillaceous rocks which have undergone induration of greater intensity than that found in shales, and which have secondary cleavage developed to a much greater degree than in shale but to a much less degree than in slate.

the rock is of Silurian age. It may fall somewhere in the sandstone-conglomerate-shale sequence already described, in which case it would be necessary to postulate that somewhere in the region certain strata of this sequence pass laterally into limestone. The writers prefer to assume that the limestones lie above the Pike formation, though there is little actual proof of this except the fact that the limestone contains no clastic material. No name is applied to the limestone because it has not been seen in a natural exposure.

IGNEOUS ROCKS

Ordovician and Silurian strata in the region around Notre Dame Bay have been more or less affected by bodies of igneous rock. Dikes cut the Silurian of Yellow Fox Island, on the headland where Botwood lies, and at Grand Falls on Exploits River. Sills are in strata of the same age on Yellow Fox Island, and a flow breccia on Upper Black Island contains blocks of fossiliferous Silurian limestone. So far as known, no contemporaneous volcanic rocks have been found in Silurian strata, though it is altogether possible that some of the various igneous bodies entered the beds in late Silurian time.

Besides the numerous minor intrusives, there are at least four igneous bodies of batholithic proportions in the region of Notre Dame Bay. Two of these are composed of granodiorite and have been designated the Loon Bay and the Long Island batholiths by Heyl.[9] The third and fourth constitute a large part of Fogo Island and a large part of Twillingate Island. The lithology of the last two does not seem to have been studied to any extent. Many of the dikes of the region are known to be genetically related to the batholiths, from the peripheries of which they radiate into the adjacent rocks. Lamprophyre dikes cut sediments, dikes, and batholiths alike, and are clearly the latest igneous materials to have intruded the rocks of the region.

The batholiths were not seen in actual contact with Silurian strata, hence their age relations with them are not directly determinable. They are certainly younger than the Ordovician rocks which they can be seen to intrude. Furthermore, they seem to have invaded the rocks of the region after the deformation which folded the sedimentary rocks (possibly contemporaneously with that orogeny), and, since this deformation appears to have affected Ordovician and Silurian strata alike, it follows that the batholiths intruded the rocks sometime after the early Silurian—the age of the only known Silurian in the region.

The extensive Acadian orogeny took place in the Maritime Provinces in late Devonian time, and it is possible that the deformation in the

[9] G. R. Heyl: *Geology and mineral deposits of the Bay of Exploits area*, Newfoundland Dept. Nat. Res., Geol. Sec., Bull. 3 (1936).

region of Notre Dame Bay was contemporaneous. There was also a post-Carboniferous movement in Newfoundland, as shown by disturbed Carboniferous strata on the west side of the island in the region of St. George Bay. Perhaps the deformation in Notre Dame Bay is of that age. Finally, on the European side of the Atlantic there was the extensive Caledonian orogeny in late Silurian time. This orogeny has also been identified in Greenland, and it may well have extended into Newfoundland. The fact that the Silurian of Newfoundland represents only the early part of the period suggests that uplift took place shortly thereafter, and this uplift may have been precursory to the Caledonian orogeny. The conglomerates in the section indicate that an elevated land was the region of supply, and, as these overlie the sandstones, it follows that elevation of the source rocks probably was in progress during the early Silurian. It is Heyl's opinion [10] that the orogeny of north-central Newfoundland, as indicated by the deformation of Ordovician and Silurian strata, is best correlated with the Caledonian orogeny, and the present writers are in accord with that view.

SILURIAN CONGLOMERATES

Thick conglomerates make up a considerable part of the known Ordovician and Silurian sections. Some of the Silurian conglomerates contain fossils in thin layers of interbedded limestone and calcareous argillite, but most are barren. The Ordovician conglomerates contain a few fossils. The best development of the Silurian conglomerates is in Goldson Arm and vicinity, New World Island, and the writers have proposed, therefore, to apply the name Goldston formation to these conglomerates.

The northeastward-trending ridge on the south side of Goldson Arm, which is joined to the mainland by Herring Neck (Fig. 4), is composed largely of conglomerate. A section of sandstones and conglomerates, more than 600 feet thick, was measured across the northeastern end of this ridge. The strata dip southward at a high angle, and the sequence appears to be continuous southward as far as a probable fault zone. South of this zone is a second sequence of sandstones and conglomerates essentially similar to those to the north, with a thickness of about 340 feet. If these two sequences are distinct, then the conglomerate formation is nearly 1000 feet thick. It is possible, however, that the fault may duplicate or eliminate some of the beds.

On the approach to and along the canal joining Pike and Goldson arms, there is over 150 feet of conglomerate markedly different from those just described, in that the components are mainly dark basic igneous rocks ranging in dimension from small pebbles less than an inch in diameter

[10] *Ibid.*

to large boulders several feet across. The matrix is decidedly red, appears to consist mainly of arenaceous and argillaceous material, and exhibits no evident stratification.

All the islands and peninsulas in Pike Arm, except the peninsula designated "Fossil Point" (Fig. 4), and the coasts on both sides of the arm are composed of conglomerate. Herring Head, which seems to be a continuation of the ridge of Herring Neck, extends seaward as a bold, precipitous headland and is essentially a solid mass of crudely bedded, yellowish gray conglomerate dipping to the southeast at a high angle. The Luke Arm thrust of Heyl passes along the north side of the headland. The conglomerate in Herring Head is approximately 900 feet thick, and there appears to be no duplication by faulting. An additional 150 feet of conglomerate, like that exposed along the canal between Pike and Goldson arms, is present on a small peninsula extending from Herring Head into Pike Arm. This gives a total of 1050 feet of conglomerate. The conglomerates exposed on the islands in Pike Arm may increase this figure, but, since there are numerous faults in the arm, it seems likely that some, if not all, of the conglomerates on the islands are the same as the conglomerates exposed in Herring Head. There is a fault on the south side of Pike Arm with the hanging wall to the south. At least 1000 feet of conglomerate is exposed south of this fault. It is postulated that this conglomerate duplicates that in Herring Head. While it is not positively known that these conglomerates are Silurian, the fact that they are on the strike of conglomerates containing Silurian fossils and having similar characters renders it extremely probable that they belong to that system.

The conglomerates forming Herring Head, as well as the numerous exposures in Pike and Goldson arms, generally contain few boulders larger than a foot in greatest dimension. The red conglomerate along the canal between the two arms and on the peninsula projecting from Herring Head into Pike Arm has somewhat larger boulders. Most components range from 1 to 5 inches in greatest dimension and show considerable rounding. Basic igneous rocks constitute from 70 to 90 per cent of the components. There are also a few particles of granite, pink and red quartzite or rhyolite, and an occasional small pebble of chert or jasper. Bedding is obscure in most places; consequently the attitude ordinarily is difficult to determine.

The Silurian conglomerates vary laterally in texture, but the variation does not seem to be so great as in the Ordovician conglomerates exposed on West Indian Island and at Port Albert (Fig. 1). Although individual beds may change laterally to some extent, the conglomeratic units as a whole retain a somewhat persistent lithology and thickness.

SECTIONS IN NOTRE DAME BAY AND VICINITY

BOTWOOD

General Statement.—The exposures investigated in the Botwood region lie along the northwest bank of the Exploits River at Martin Eddy Point, and along the shores of Exploits Estuary as far north as Northern Arm (Fig. 2). The western shore was traversed by pacing and compass and the thicknesses computed from strikes and dips.

The Exploits Estuary, in the vicinity of Botwood, transects the strike of the strata, but its tributary arms as well as long stretches of Exploits River trend northeastward in harmony with the regional structure. A prominent ridge parallels Norris Arm on the southeast. This is composed of basic igneous rock flanked along the northwestern face by Ordovician (?) slates dipping steeply southeastward toward the igneous body. The rock on the southeastern side of the ridge is unknown. Numerous quartz veins, some as much as 3 feet wide, cut the slates. The slates were not seen in contact with the igneous rock, but conditions suggest that the latter is intrusive.

So far as investigated, the structural conditions from Norris Arm to Northern Arm are in harmony with a large anticline trending northeastward. The strata exposed along the western shore of Exploits Estuary from Wigwam Point to Peter Arm lie on the southeastern flank; those from Peter Arm to Northern Arm on the northwestern (Fig. 2). It is suggested that a fault on the southeast side of Norris Arm separates these Silurian strata from those of the Ordovician. The strata on the southeastern limb of the fold seem little disturbed, but those on the northwestern limb have been intruded by dikes and are considerably disturbed. A cross-section of this postulated anticline is shown in Figure 2.

The strata exposed along the western shore of the Exploits Estuary are mainly red and pink, cross-laminated sandstones which are not greatly metamorphosed. The sandstones apparently are barren, but the overlying conglomerates contain numerous fossils of Silurian age. The total thickness of the exposed section approximates a mile. This sandstone is designated the Botwood formation, with its type section along the western shore of the Exploits Estuary between Wigwam Point and Peter Arm.

Wigwam Point to Peter Arm.—The section that follows was measured in descending order from Wigwam Point northward along the west coast to Peter Arm (Fig. 2). The highest strata are fossiliferous Silurian conglomerates exposed at Martin Eddy Point on Exploits River about 2 miles above Wigwam Point. Similar conglomerates, in which no fossils were found, are exposed on the east shore of Exploits Estuary beginning at Norris Arm. Underlying the conglomerates of Martin Eddy Point (= Goldson conglomerates of New World Island) are the red, cross-laminated sandstones of the Botwood formation. The cross-lamination shows that the beds are in an upright position, and they appear to lie on the southeast limb of an anticline of which the axial region is believed to be concealed beneath the waters of Peter Arm. North of Botwood, cross-lamination again shows the sandstone beds to be in upright position, but here the dip is in the opposite direction—that is, to the northwest—hence these strata lie on the northwest limb of the postulated anticline (Fig. 2).

The exact relations of the conglomerates and sandstones are not clearly shown because a large concealed interval separates them. It is believed, however, that the conglomerates overlie the sandstones, because of the many blocks of fossiliferous conglomerate on the first small point north of Wigwam Point in close proximity to exposures of sandstone, and the presence of similar blocks of conglomerate in

Northern Arm in the same position with respect to the sandstone, but on the other side of the anticline.

The section as here given has an approximate thickness of 5800 feet exclusive of the horizon assigned to the conglomerates, which may aggregate an additional 1000

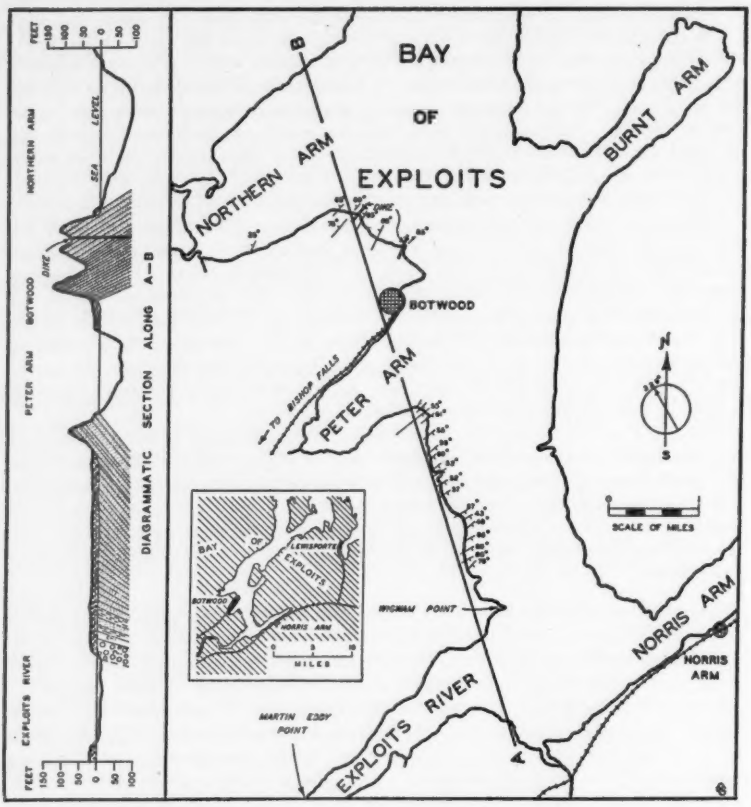

FIGURE 2.—*Map of the Botwood region, Bay of Exploits*

Showing some of the geology, and diagrammatic section through the postulated anticline along the western shore of the estuary. Figures indicate degrees of dip. Based on United States Hydrographic Office Chart No. 1101 (1923).

feet. It is possible that there is some repetition or concealment of strata due to faulting, but the lowest 2000 feet is almost continuously exposed and there is little or no suggestion of faulting where the strata are not exposed, so that the possibility of repetition or concealment due to this cause seems remote. The sandstones bear an extremely close resemblance to those of Change Island and those on the Ex-

ploits River at Grand Falls and Bishop Falls. From Wigwam Point to Peter Arm, the section is as follows, in descending order:

Zone	Feet
4. Conglomerate, shale, and siltstone, all considerably metamorphosed.....	?1000

The strata in the Martin Eddy Point exposure strike N 20° E and dip[11] southeastward at about 72°. At the entrance to Norris Arm on the northwest shore about 175 feet of conglomerate is exposed with strike about N 50° E and dip about 55° SE. Half a mile farther north along the shore is an exposure of about 30 feet of similar conglomerate. The attitude of the rock is not in harmony with that at Martin Eddy Point and at the entrance to Norris Arm, and faulting is believed to have taken place. Half a mile farther north there is an exposure of reddish slate and sandstone with some conglomerate. It is not known that any of the strata along the east side of the estuary fall in any part of the concealed zone assigned to the conglomerate. The detailed section at Martin Eddy Point in supposedly descending order is as follows:

d. Conglomerate, mainly small pebbles about 1 inch in diameter. Some boulders of a black rock are as much as a foot long. A few of the components are composed of vein quartz, but most are composed of a dark-blue rock	25
c. Argillite, hard and grayish blue, containing fossiliferous boulders.....	9
b. Conglomerate like *d*.....	10
a. Argillite, grayish blue.....	4

The following fossils were collected by the various expeditions from Princeton University and by the present writers at Martin Eddy Point from boulders and matrix:

Fucoids, probably algal
Clathrodictyon vesiculosum
Favosites gothlandicus
Favosites cf. *pyriformis*
Zaphrentis cf. *stokesi*
Echinoderm columnals, probably crinoidal
Hallopora? sp.
Parmorthis elegantula
Chonetes n. sp.
Cœlospira hemispherica
Atrypa reticularis
Lissatrypa? cf. *atheroidea*
Rhynchotreta cuneata
Worm? tubes
Diaphorostoma? sp.
Pleurotomaria sp.
Leperditia sp. and some small ostracods
Encrinurus anticostiensis

Large blocks of conglomerate like those at Martin Eddy Point are common on the first point north of Wigwam Point (Fig. 2), and thence north for a short distance along the shore. From these blocks were collected the following:

Clathrodictyon vesiculosum
Cyphotrypa sp.
Hallopora cf. *elegantula*
Echinoderm columnals, probably crinoidal

[11] All bearings are given in terms of true north, hence they have been corrected for the 31-degree declination of the Bay of Exploits region.

Zone	Feet
3. Argillite, sandstone, and slate. This zone is composed of alternating argillites, gray sandstones, and dark slates. The rocks are only intermittently exposed, and few outcrops show more than 15 feet. The strike of the strata ranges from about N 40° E to N 60° E, and the dip from nearly vertical to a steep southeasterly inclination. No fossils were seen in this unit.	1300
2. Sandstone. This zone consists of fine-grained, ripple-marked, cross-laminated, fairly thin-bedded (6 inches to 2 feet), red sandstones. The exposures are intermittent. The cross-lamination shows that the top of the beds is to the southeast. No fossils were seen. Strike, about N 50° E; dip, about 60° to the southeast.	2500
1. Sandstone. The rocks of this zone are continuously exposed either on the shore of, or in the hills above, Peter Arm. They consist of fine-grained, thin-laminated, cross-laminated, ripple-marked, red sandstone. The strike approximates N 45° E and the dip is consistently to the southeast at an angle of from 50° to 60°. The cross-lamination shows that the strata are in normal position.	2000
Total thickness, approximately	6800

Botwood to Northern Arm.—The section between Botwood and Northern Arm is largely composed of thin-bedded, red sandstones and dark argillites. These strata are cut by two basic dikes and are somewhat more metamorphosed than equivalent beds lying south of Peter Arm (Fig. 2). The strata dip consistently northwestward and form the northwest limb of the postulated Botwood anticline. The section is not continuous, and the concealed intervals exceed the exposed. The thickness is estimated at 5300 feet, but faulting may duplicate or conceal some beds. The section contains several disturbed zones, and there are local reversals of dip. Several large blocks of fossiliferous conglomerate were found near the northernmost exposures of sandstone (and hence stratigraphically higher than the sandstone), thus duplicating the conditions at Wigwam Point. From Botwood to Northern Arm, a section is as follows:

Zone	Feet
4. Sandstone. This zone is composed of fairly thick-bedded, cross-laminated sandstone dipping about 25° northwest. The exposures are intermittent.	500
3. Concealed interval. No strata are exposed in this interval, but the beach is strewn with blocks of red sandstone similar to that of zone 4. Several large blocks of conglomerate like that at Martin Eddy Point were also found and are believed to have come from some horizon above zone 4. From these blocks were collected *Clathrodictyon vesiculosum* and *Zaphrentis* sp.	1350
2. Sandstone. Cross-laminated, ripple-marked, fairly thin-bedded, red sandstone. This rock is intermittently exposed with continuous sections rarely exceeding 100 feet in thickness. The strata strike N 20°-40° E and dip from 65° to 75° to the northwest. The cross-lamination shows that the strata are in upright position. The zone is cut by an 18-inch dike that trends about N 40° E and is essentially vertical.	3400
1. Red rock resembling quartzite. This zone is composed of red, brittle rock that is much fractured and is cut by a 2-foot, biotite-bearing, black basic dike, which seems to be essentially vertical.	60
Total thickness, approximately	5300

UPPER BLACK ISLAND

One of the most interesting occurrences of the Silurian in the Notre Dame Bay region is on Upper Black Island near the entrance to the Exploits Estuary (Fig. 1). This island is composed largely of basalt, which is of Breakhart age according to Heyl.[12] On the northeast corner of the island, at the contact of the basalt with black slates, is an igneous mass which is interpreted as a basaltic flow breccia. The black slates contain Normanskill graptolites, and hence are of Ordovician age. The contact of the flow breccia with the slates is along a fault. The breccia contains blocks of very hard, highly metamorphosed, crystalline limestone which are as much as 5 feet in greatest dimension. Most of the blocks have been so thoroughly recrystallized that any fossils once present have been completely destroyed, but several show the presence of organic remains, and three were found in which the fossils are fairly well preserved. One of the fossiliferous blocks contains an abundance of a single species of *Stricklandinia*. The beaks of the shells seem dominantly to be directed upward, suggesting that the block is upside down. Associated with the shells are poorly preserved fragments of two cephalopods. Other blocks were seen in which the same brachiopod appears to be present, but the rock is too metamorphosed for certain determination. An 18-inch, somewhat spherical block with concentric structure, and possibly a *Clathrodictyon*, was found just below the block containing the brachiopods. Echinoderm columnals, probably crinoidal, were noted in one of the blocks.

The flow breccia can be followed for 125 to 150 feet along the shore and 20 to 25 feet of it is exposed through a thickness perpendicular to the coast. The original surface over which the flow moved seems to be nearly vertical with strike parallel to the shore.

Blocks of limestone in the flow breccia prove that it is of post-early Silurian age and that it is not a part of the Ordovician, with which it is in contact. The age of the main basaltic body, of which most of Upper Black Island is composed, remains to be determined. Perhaps it is the equivalent of the Breakhart basalt with which it is correlated by Heyl, or it may have the same general time relations as the flow breccia.

YELLOW FOX AND INDIAN ISLANDS

General Statement.—The section now to be described consists of four separate parts, as shown in Figure 3. The highest beds constitute Yellow Fox Island; the second part in descending order is the section across East Indian Island; the third part is that in a small island north of East Indian Island and in the narrow peninsula at the southeast corner of West Indian Island; and the lowest beds, exposed along the eastern shore of West Indian Island, constitute the fourth part of the composite section. There are two concealed zones in this sequence of which nothing is known—one between Yellow Fox and East Indian islands, the other between the two Indian islands. Since the strike of the strata in the three islands is essentially uniform, it is assumed that the section is continuous, though it must be emphasized that the concealed intervals may hide rocks or faults which break the succession. There is no evidence in the exposed part of the section of any significant stratigraphic break, and to this extent the succession seems to be continuous. The strata of East and West Indian islands are referred to the Ordovician, though no fossils have been found to make this reference certain. The strata of Yellow Fox Island are of Silurian age as shown by the fossils. The contact between the Silurian and the Ordovician is assumed to lie in the concealed interval between the lowest strata of

[12] G. R. Heyl: *op. cit.*

Yellow Fox Island and the highest strata in East Indian Island. The strata of both systems are greatly metamorphosed in all exposures, with the argillaceous beds now represented by silky, phyllitic slates and the sandstones by quartzites. Dark

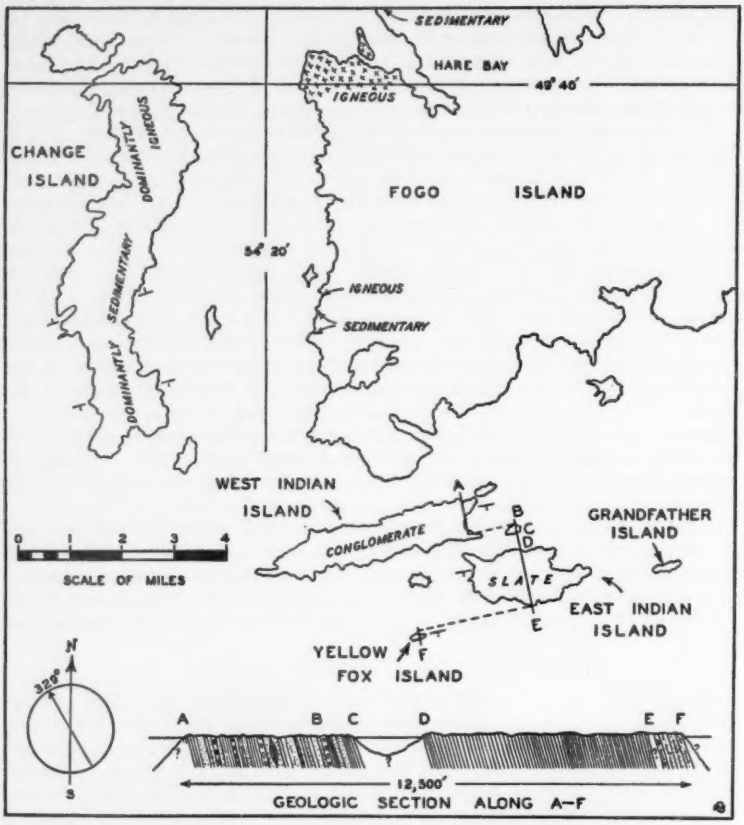

FIGURE 3.—*Map of several large islands in Notre Dame Bay*

An anticline is indicated in southern part of Change Island; several areas of igneous and sedimentary rocks are shown on Fogo Island; geology of Indian and Yellow Fox islands is shown. The different parts of the section measured on Indian and Yellow Fox islands are indicated, and a geologic section shows the nature of the strata. Based on United States Hydrographic Office Chart No. 1101 (1923).

sills and dikes are present throughout the section, and locally there are numerous quartz veins, particularly in association with the intrusives.

Yellow Fox Island.—Yellow Fox Island is a low, small mass of rock lying about 1½ miles southwest of East Indian Island and about the same distance south of West Indian Island. If the strike of the lowest strata exposed along the north side were projected, the line would probably come close to the highest strata exposed

along the south side of East Indian Island. The strata strike in harmony with the island's longest dimension, which is nearly east-west (Fig. 3). They stand in nearly vertical position, dipping steeply southward, and are intruded by several dikes and sills. The section of the island, presumably descending as indicated by the relation of cleavage to bedding, is as follows:

Zone	Feet
13. Basic intrusives and slate	89

This division has a basic dike 25 feet thick at the top and one 28 feet thick at the base. The intermediate slate is 36 feet thick, strikes about N 70° E, and is dark-gray with a silky luster.

12. Slate	463

The rock is generally dark-gray or locally reddish gray and has a silky luster. The strike is about N 65° E and the dip 85°-90° S. There is a 3-foot basic dike near the middle of the sequence.

13. Sandstone and slate	166

This division is composed of three units, of which the highest is 25 feet thick and composed of granular to fine-grained, light-gray, calcareous sandstones interbedded with gray, silky sandstone and slate, with two lenticular bodies of dark igneous rock. The sandstone beds range in thickness from 6 inches to 3 feet and contain greatly sheared and recrystallized Silurian corals. The middle unit is 57 feet thick and consists of dark-gray, silky slates with two lenticular dikes of basic igneous rock (one from 1 to 4 feet thick; the other from 4 inches to 2 feet thick). The lowest unit is composed of gray, silky slates and subordinate calcareous, gray sandstones. Both slates and sandstones are much sheared and contain Silurian corals. The following species have been identified from this horizon:

Clathrodictyon vesiculosum
Cyathophyllum cf. *articulatum*
Favosites gothlandicus
Favosites hisingeri
Zaphrentis cf. *stokesi*

10. Basic igneous rock with some slate	240

This zone is composed mainly of dark dikes and sills. The slates are dark gray and silky. The strata strike N 75° E and dip 80° to 90° S.

9. Concealed zone

The concealed zone, 1½ miles from the northern side of Yellow Fox Island to the southern shore of West Indian Island, is thought to contain the strata present on East Indian Island. Whether the section is continuous is uncertain, but it seems probable that some structural weakness accounts for the cutting of the depression between the two Indian islands.

As already stated, if the strike of the northernmost beds on Yellow Fox Island be projected eastward, the line would come close to the southern shore of East Indian Island.

Indian Islands.—The Indian islands are low and have little vegetation other than swamp; there are no exposures inland and no high cliffs along the shore, but the broad tidal zone allows extensive exposure of rocks at low tide. The strata strike with the longer dimensions of the islands and dip consistently southward at angles that approach the vertical (Fig. 3). The thicknesses were determined by pacing perpendicular to the strike and then computing from the dip. Well-developed drag-folds along the western shore of East Indian Island suggest that the top of the beds is to the south and that they have not been overturned. The section, assumed to be in descending order and stratigraphically below the strata of Yellow Fox Island, is as follows:

Zone		Feet
8.	Slate	4700

This great slate unit forms East Indian Island, where it is well exposed along the shores. The rock is a gray, silky slate with excellent cleavage and numerous drag-folds; the structural features are particularly well developed on the south and west shores. The upper part of this division contains numerous small, very hard and tough, blue, calcareous bodies like the septarian calcareous bodies found in association with the argillites and conglomerates in Goldson Arm, New World Island. No fossils were found in any part of the unit.

7.	Concealed interval	(estimated)	1450

This interval represents the channel between the two Indian islands. The thickness of strata concealed beneath the water was estimated from the strikes and dips on the two sides of the channel and the horizontal distance across it, as given by the British Admiralty Chart of the islands. It is assumed that the concealed strata are continuous with those above and below, but of this there is no definite proof.

6.	Slate, argillite, and quartzite	1450

The strata of this zone are dark, silky slates with thin, interbedded argillites and quartzites. The upper 650 feet is characterized by numerous lenticular bodies of basic igneous rock that are interpreted as sills. They range in thickness from 6 inches to 3 feet and are as much as 20 feet long. It is also possible that these bodies may be basic, arenaceous lenses altered by metamorphism. The slaty laminae bend around the lenticular bodies as though they had been spread apart.

5.	Conglomerate, quartzite, and slate	600

This zone is composed of alternating successions of conglomerates, gray silky slates, and gray quartzites. One conglomeratic unit, 125 feet thick and near the base of the zone, contains numerous lenticular bodies of basic igneous rock similar to those of zone 6. The components of the conglomerates are mainly discoidal and are as much as 5 inches in diameter. All are arranged parallel to the bedding. The strike of the strata is about parallel to the longer axis of the island (West Indian) and the dip is about 82° to the south.

4.	Slate and quartzite	800

This zone consists of an upper silky slate unit 660 feet thick, separated from similar rock at the base by a 40-foot unit of gray, medium-grained sandstone (quartzite) interstratified with gray silky slate. The strata dip from 75° to 82° to the south.

3.	Conglomerate, slate, and quartzite	350

The rock of this zone is similar to that of zone 4 except that there is somewhat more quartzite, some of which is coarse-grained and grades laterally into conglomerate. The sequence is cut by several dark basic dikes.

2.	Basic igneous rock, apparently a flow	150
1.	Quartzite and slate	150

The succession in this zone consists of dark-gray quartzite at the base, passing upward into gray slate with many lenses of quartzite. The section ends on the north shore of West Indian Island.

Total thickness, approximately	10,600

CHANGE ISLAND

Excellent and extensive exposures are found on most parts of the coast of Change Island. The southern half of the island is composed largely of little-altered sandstones, whereas the northern half consists of greatly metamorphosed igneous and

sedimentary rocks. In the southern fourth of the island there is a broad anticlinal structure trending northeastward across the island (Fig. 3) and dipping as steeply as 55 degrees on its flanks. Approximately 2000 feet of fairly thick-bedded, cross-laminated, medium-grained, gray sandstone was measured on the flanks of this structure. Echinoderm columnals, probably crinoidal, were seen in the sandstone at the southeast corner of the island where the telegraph line enters the water. No other fossils were found. These sandstones are similar to those at Grand Falls on the Exploits River and in the Botwood sections, and are referred to the Botwood formation.

The sandstones of Change Island are cut by several basic intrusives, of which some may be sills. Northward the anticline ends at a fault, beyond which lies a thick sequence of pyroclastics, flows, flow breccias, and greatly altered slates. The thickness of these rocks must be great, but the complexity of the structure precluded determining it. These rocks seem to be more metamorphosed than the Silurian sandstones and are, therefore, referred to the Ordovician.

LONG TICKLE

Long Tickle is south of Cobb Arm, New World Island (Fig. 4). A thick section of conglomerates, arkosic quartzites, and slate is present. It was at first thought that the quartzites and conglomerates of this section might be referred to the Silurian, but it is now considered more reasonable that they are of Ordovician age. A thickness of 1325 feet was measured along the eastern or main branch of Long Tickle. Islands just off shore, in the entrance to Cobb Arm, show an additional 300 feet of the same kind of rock. On the south side of the junction between the two branches of Long Tickle there is 500 feet more, giving a total of more than 2100 feet. The beds strike approximately N 60° E and dip almost vertically. South of these strata, 2000 to 3000 feet of slate have about the same attitude.

The beds of conglomerate and quartzite are thick, with the former as much as 15 feet and the latter up to 20 feet. The conglomerate is generally composed of small particles with maximum dimensions of 2 to 3 inches, but some components are as large as 10 inches across. Exposed surfaces of these strata have a reddish appearance when seen from a distance, but close examination of the rock, especially if freshly broken, shows it to have a gray matrix filled with grains of red feldspar. No fossils were found in any of these strata, but Normanskill graptolites have been collected from slates in Cobb Arm. The writers found a single cephalopod in the slates directly opposite the limestone (marble) quarry at the bottom of the arm. A. K. Miller has examined the specimen and suggested that it should probably be referred to the Normanskill genus, *Michelinoceras*.

GOLDSON AND PIKE ARMS

General Statement.—The exposures in Goldson and Pike arms, New World Island, are of great importance because of the unusual development of Silurian conglomerates and the abundance of fossils in some of the associated strata. The fossiliferous strata are exposed on, and in the vicinity of, Burnt Island in Goldson Arm, and on "Fossil Point"—a peninsula in Pike Arm.

Burnt Island.—Burnt Island is composed of red sandstones, coarse conglomerates, and black, more or less calcareous argillites. The backbone of the island is conglomerate, and most of the shore is sandstone. The structure appears to be that of an anticline trending parallel to the long dimension of the island, though this structure is considerably complicated by faulting. Two fossiliferous horizons are present—one lying in a black argillite, the other in a dark-gray, calcareous, coralline

argillite. The former is exposed on the north side of the island and is bounded, so far as can be determined, by faults; hence its stratigraphic relations with the adjacent red sandstones is not known. The rock is greatly sheared, and the fossils are more or less distorted. The exposed thickness approximates 50 feet, but the fossils seem to be limited to a few layers. The argillite also contains numerous, very hard and tough, calcareo-siliceous, septarian-like nodules.

The second abundantly fossiliferous horizon on Burnt Island lies in a calcareous argillite exposed along the east shore just south of the large mass of conglomerate forming the backbone of the island. The fossils are mainly corals and brachiopods. The fossiliferous strata may be as much as 50 feet thick. What seems to be this same argillite is found little disturbed on the southeast side of the prominent headland northeast of Burnt Island.

With the exception of small exposures of argillites and conglomerate, the coastal rocks of Burnt Island are red sandstones. The thickness of these sandstones is estimated to be somewhat less than 500 feet. The rocks contain numerous echinoderm columnals and a few brachiopods and corals. They seem to be overlain by conglomerate, which probably does not exceed 100 feet in thickness. A dark slate containing poorly preserved fossils is exposed in a fault block at the extreme western point of the island.

In a general way the strike of the strata composing Burnt Island is essentially parallel to the longer dimension of the island, and the dip is rather consistently southeastward except where disturbed by faulting or drag folding. The presence of at least five important faults makes it extremely difficult to reconstruct the section, but it is thought to be the same as that measured on the southern shore of Herring Neck.

The fauna from the black argillite along the north side of Burnt Island contains the following:

Coenites labrosus
Lyellia ? affinis
Enterolasma calycula
Zaphrentis cf. *stokesi*
Echinoderm columnals, probably crinoidal
Lingula sp.
Parmorthis cf. *elegantula*
Leptaena rhomboidalis
Rhynchotreta cuneata
Cœlospira hemispherica
Atrypa reticularis
Cornulites sp.
Pterinea emacerata
Bellerophon sp.
Cyclonema? sp.
Gyronema? sp., low spired
Gyronema? sp., high spired
Hormotoma? cf. aculeata
Orthoceras sp., with fine annulate striae
Kionoceras bellatulum
Amphicyrtoceras? cf. *futile*, doubtful
Leperditia sp., probably n. sp.
Calymene niagarensis
Illaenus or *Bumastus* sp.
Encrinurus anticostiensis
Eophacops n. sp.

The coralline argillite along the east shore of Burnt Island has yielded the following:

Clathrodictyon vesiculosum
Halysites catenularia
Favosites gothlandicus
Coenites labrosus
Zaphrentis cf. *stokesi*
Echinoderm columnals, probably crinoidal
Cyphotrypa? sp.
Dolerorthis flabellites
Leptaena rhomboidalis
Cœlospira? hemispherica
Spirifer cf. *radiatus*

South Shore of Goldson Arm.—The southeast shore of Goldson Arm is composed of conglomerate more than 200 feet thick. The rock is dark red and the individual components show considerable variation in lithology. They range from half an inch or less to as much as 2 inches in greatest dimension. All seem to be well rounded and firmly cemented in the arenaceous or argillaceous matrix. The succession is composed almost entirely of conglomerate, though there are a few thin bands of sandstone and argillite. Lenticular bodies of calcareo-siliceous material, having some of the characteristics of septaria, are not infrequent between the beds of conglomerate and contain most of the fossils found in the succession. The following have been identified:

Clathrodictyon vesiculosum
Favosites gothlandicus
Zaphrentis cf. *stokesi*
Pentamerus oblongus
Schuchertella pecten

Similar calcareous lenses, found in a conglomerate on a small island near the bottom of Goldson Arm, yielded the following:

Clathrodictyon vesiculosum
Favosites gothlandicus
Favosites hisingeri
Pentamerus sp.
Diaphorostoma? sp.

Southeast Shore of Herring Neck, Southwest End.—The section that follows was measured on the southeast side of the prominent headland forming the southwest extension of Herring Neck (Fig. 4). This headland is in direct line with Burnt Island, and the conglomerates and sandstones of which it is composed are considered equivalent to those on that island. The strike of the strata parallels the trend of the headland, which is northeast-southwest, and the dip is 75° to the southeast. The succession, presumably in descending order, is as follows:

Zone		Feet
5.	Siltstone and sandstone	approximately 500
	This zone consists of red siltstone and gray, fine-grained sandstone. The beds are more or less crumpled, and may end against a fault to the south. These strata are well exposed near the northeastern end of the small bay separating this part of Herring Neck from the mainland. No fossils were noted in this unit.	
4.	Conglomerate	25
3.	Sandstone	280
	This sandstone is red, fine- to coarse-grained, and passes downward into interbedded sandstone and argillite.	
2.	Argillite containing corals	9
	Fossils collected from this zone, in addition to the common corals found on Burnt Island, are:	
	Coenites labrosus *Brachyprion robustum* *Schuchertella pecten* *Encrinurus anticostiensis* *Illaenus* or *Bumastus* sp.	
1.	Conglomerate	more than 40
	Since the lowest exposures of this section are on the south shore of the headland, which appears to be composed almost entirely of conglomerate, it follows that zone 1 is probably hundreds of feet thick. What is thought to be the equivalent of zone 1 is given in the section measured across the northeast end of Herring Neck (Fig. 4).	
	Total thickness, probably much greater	854

Herring Head.—The bold headland of Herring Head (Fig. 4) is composed of a great thickness of conglomerate, to the resistance of which it owes its trend and existence. Southwestward this same conglomerate, apparently, forms the ridge of

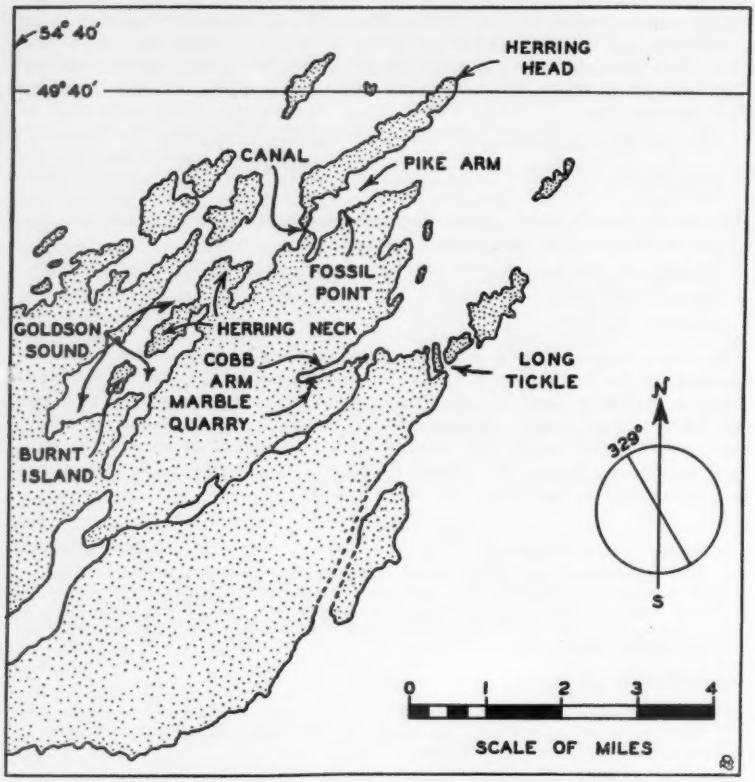

FIGURE 4.—*Map of a portion of New World Island*

Showing relation of numerous headlands and arms in the vicinity of Herring Head, Pike Arm, and Goldson Arm. Fossiliferous localities and measured sections are indicated. Based on United States Hydrographic Office Chart No. 1101 (1923).

Herring Neck. Measurement by pacing showed that there is more than 900 feet of crudely bedded conglomerate in Herring Head and the active erosion going on along the northwestern side of the headland suggests that a considerable thickness has probably been removed. The conglomerates strike northeastward with the trend of the headland.

If to the 900 feet of conglomerate just described is added the 150 feet of red conglomerate exposed along the canal between Pike and Goldson arms, the total

known thickness of the conglomerate formation, to which the name Goldson has been applied, will approximate 1050 feet. This figure is almost certainly conservative, because the writers have measured a 1000-foot section of coarse sandstone and conglomerate in the northeast end of Herring Neck (Fig. 4). This sequence, considered the equivalent of the Goldson formation of Herring Head, is separated into an upper zone 340 feet thick and a lower zone somewhat more than 600 feet thick, by a structural contact which may be a fault. No fossils were found in the conglomerates of Herring Head and Herring Neck.

Pike Arm.—Pike Arm is the locus of a large fault by which the Goldson conglomerates of Herring Head are duplicated on the south side of the arm. The fault scarp is exhibited prominently at numerous points along the southern shore. All the islands in the arm are composed of conglomerate except the island and peninsula designated "Fossil Point" (Fig. 4), in which, besides conglomerate, there is a considerable thickness of fossiliferous argillite. This point has a low area which is flooded at high tide, making part of the peninsula an island. The section that follows was measured along the northwestern, northern, and northeastern sides of the peninsula, terminating at the steep fault scarp along the southeastern side of Pike Arm. This scarp, forming the northwestern boundary of the hanging wall, dips southeastward 75° and parallels the south side of the arm for several miles.

The argillites and sandstones exposed on Fossil Point are designated the Pike Arm formation, and the type section is that on the point just mentioned. This formation is thought to overlie the Goldson conglomerates.

The section starts at the fault scarp and is presumably descending, though of this there is no definite proof. Thicknesses are partly estimated.

Zone	Feet
7. Argillite	300+

This argillite is very dark, contains septarian-like nodules, and has a few poorly preserved fossils.

6. Argillite and sandstone	150

The argillite is black, contains septarian-like nodules similar to those in zone 7, and has a few poorly preserved fossils. The sandstones make up only a minor portion of the sequence. This sequence ends at the low area across the peninsula.

5. Argillite	75

This zone is composed of an argillite that breaks into irregular fragments, contains numerous septarian-like nodules, and is quite fossiliferous with the fossils fairly well preserved. The following species were identified from this zone:

Cyathophyllum cf. *articulatum*
Enterolasma calycula
Zaphrentis cf. *stokesi*
Echinoderm columnals, probably crinoidal
Orbiculoidea sp.
Dolerorthis flabellites
Sowerbyella transversalis
Leptæna rhomboidalis
Brachyprion anticostiensis
Brachyprion robustum
Brachyprion leda
Stricklandinia sp.
Plagiorhyncha decemplicata
Eospirifer radiatus
Coelospira hemispherica
Cornulites serpularius
Pterinea emacerata
Sinuites sp.
Salpingostoma cf. *orientalis*
Gyronema? sp.
"Orthoceras" sp.
Illaenus or *Bumastus* sp.
Eophacops sp.
Encrinurus anticostiensis

Zone	Feet
4. Argillite	6–8

This zone consists of a dark-gray, somewhat coralline argillite, which is designated the second coral zone (the first coral zone is zone 2). Fossils identified from this argillite include:

Halysites catenularia
Heliolites subtubulatus
Favosites hisingeri
Favosites gothlandicus
Cyathophyllum cf. *articulatum*
Zaphrentis cf. *stokesi*

3. Sandstone and conglomerate, in thick beds	210
2. Argillite, crowded with corals (first coral zone)	100

The rock of this zone is dark-gray argillite in which there is an unusually large number of fairly well preserved corals. The strata dip in a southerly direction at an angle of about 70° and strike about N 60° E. The following fossils were collected from this zone:

Clathrodictyon vesiculosum
Halysites catenularia
Lyellia affinis
Lyellia americana
Plasmopora petalliformis
Favosites forbesi
Favosites gothlandicus
Favosites hisingeri
Zaphrentis cf. *stokesi*
Atrypa reticularis
Cyclonema? sp.
Encrinurus anticostiensis

1. Sandstone and slate	150

Both types of rock are dark. The thickness is estimated, and may be much more than the figure given.

Total thickness, approximately	993+

GRAND FALLS

The sections at Grand Falls and Bishop Falls were the only ones in the interior of Newfoundland that were studied. The exposures at Bishop Falls are not extensive, and the rock is like that at Grand Falls. The section at the latter locality extends downstream from the dam near the paper mills to the large greenstone bodies which formed the crest of the original falls many thousands of years ago. The section was measured along the north wall of the river gorge, starting near the dam where the strata are not greatly disturbed. Downstream from the dam below the first occurrence of igneous rock, however, the strata are considerably disturbed for several hundred feet to the contact with a dark, fine-grained, feldspar porphyry. There are no exposures for a mile or more downstream from this rock. Interesting minor drainage changes have taken place where these igneous rocks are exposed, with abandoned channels and potholes showing where fast water once eroded the rock. The strata strike about N 30° E and dip about 70° southeastward. Cross-lamination shows that the beds are in an upright position. No fossils of any kind were seen. On the basis of lithology the sandstone is correlated with the Botwood formation. The section is given in descending order, beginning on the downstream side of the exposure.

Zone	Feet
4. Sandstone	55

This zone is composed of gray to red, rough-bedded, poorly laminated, somewhat pebbly sandstone. The section begins at the prophyry dike already noted, and ends abruptly against a dike or sill of basic igneous rock.

3. Sandstone similar to that in zone 1	100
2. Quartzite	140

Zone	Feet
1. Sandstone	850
This zone consists of red to gray, fine-grained, thick- or thin-bedded, cross-laminated, and current ripple-marked sandstone. The beds appear thick when freshly broken, but separate on exposure into layers 6 inches or less in thickness. One mud-cracked surface was seen.	
Total thickness, approximately	1145

SUMMARY OF SECTIONS

The strata of Notre Dame Bay and the Exploits Valley assigned to the Silurian fall into three lithological divisions, which are here designated the Notre Dame Series. These, in ascending order as well as in order of thickness, are sandstones (quartzites) of the Botwood formation; conglomerates (conglomerites) of the Goldson formation; and shales (argillites) and sandstones (quartzites) of the Pike Arm formation. The oldest of these, the Botwood, approximates a mile in thickness; the Goldson conglomerates are at least 1000 feet thick and may well be as much as 1500 feet thick; and the assumed youngest formation, the Pike Arm, aggregates approximately 1000 feet. That a fourth formation, probably younger than the Pike Arm, once existed in the Notre Dame Bay region is shown by the blocks of Silurian limestone in a flow breccia on Upper Black Island. This limestone has not yet been seen in place. Since the contained fossils are approximately of the same age as those in the argillites of the Pike Arm formation, it follows that the two types of rock are not greatly separated in stratigraphic position. It is assumed that the limestone lies above the clastics and, if it does, then at some time during the Silurian, after the deposition of the clastics, conditions became such that argillaceous and arenaceous sediments were not contributed to some parts of the Notre Dame Bay region. This would indicate either that the land of the region had become so reduced that clastic sediments were no longer available, or that the shore line was so far distant or so screened by shallow water that muds and sands could not be brought to the sites of limestone deposition.

Fossils have been collected in the Silurian section from shales (argillites) of the Pike Arm formation, from sandstones (quartzites) of the Botwood formation, from conglomerates (conglomerites) of the Goldson formation, and, in addition, from the limestone of Upper Black Island, whose stratigraphic position is uncertain. They are best preserved and most common in the Pike Arm formation, and consist mainly of corals, brachiopods, mollusks, and trilobites. A few corals and brachiopods have been found in argillaceous layers, thin limestones, and septarian-like nodules in the Goldson conglomerates. Only poorly preserved echinoderm columnals and a few brachiopods or corals were found in the Botwood formation.

The great thickness of conglomerates certainly reflects unusual environmental conditions under which vast quantities of coarse sands and

gravels of varied provenances could accumulate. The presence of fossils in these rocks indicates that deposition of the fossiliferous parts took place in a marine environment. The generally crude bedding suggests rapid deposition with limited opportunity for sorting. The rounding of the components indicates that considerable transportation preceded deposition, but this may have been back and forth along a shore so that the components did not travel long distances from sources. The great thickness forces the conclusion that deposition must have been in close proximity to a rising, rugged land area and in a basin that was deepening as the sediments accumulated. It seems necessary to postulate elevation of source areas in late Ordovician or early Silurian time in order to have an available source for the gravels and sands. Possibly this postulated movement may have been connected with the Taconic disturbance of eastern United States and Canada. The available evidence respecting the stratigraphic relations of the conglomerates and contiguous Silurian strata suggests that the conglomerates lie near the top of the known Silurian rather than at the base, thus indicating that elevation of the distributive areas followed the deposition of the sandstones. Data are lacking for relating distribution of the components of the conglomerates to distributive areas. It may be that these areas lay in the vicinity of Goldson Arm, for here the conglomerates have the greatest known thickness, but, before positive statements can be made respecting sources of the gravels and sands, it will be necessary to make careful studies of the components of the conglomerates and sandstones so that actual tracing to source areas may be possible.

The Silurian strata, in contrast to the Ordovician, contain no contemporaneous volcanic rocks. Dikes and/or sills are present on Yellow Fox Island, at Grand Falls, and on Northern Arm near Botwood. The time at which the igneous bodies intruded the Silurian strata has not been determined, except that it was post-Clinton, since the fossils in the intruded rocks are of Clinton age. The time of intrusion may correlate with the Caledonian disturbance of western Europe and Greenland.

The stratigraphic relations of the Ordovician and Silurian of Notre Dame Bay and the Exploits Valley are still uncertain. There is no evidence to indicate whether the contact between the two systems is a non-conformity or a disconformity, as no place has been found where the two are in contact except along a fault.

The writers received the impression that the Ordovician strata are somewhat more metamorphosed than the Silurian, but this feeling is based on comparison of two different kinds of rocks—Silurian sandstones and Ordovician slates. If Ordovician strata are the more altered, then it follows that some deformative event took place toward the close of the Ordovician.

CORRELATION OF SILURIAN OF NOTRE DAME BAY AND THE EXPLOITS VALLEY

So far as known, fossiliferous strata have been found at ten localities in the region investigated. Fossiliferous coralline argillites and sandstones of the Pike Arm formation occur in Pike Arm, Goldson Arm, and on Yellow Fox Island. Sparsely fossiliferous conglomerates of the Goldson formation are present on the southeast shore of Goldson Arm and at Martin Eddy Point on Exploits River. Richly fossiliferous argillites of the Pike Arm formation are present on Burnt Island in Goldson Arm and on Fossil Point in Pike Arm. The red sandstones of the Botwood formation contain poorly preserved echinoderm columnals on Change Island and on Burnt Island. Blocks of limestone in flow breccia on Upper Black Island contain Silurian fossils.

The stratigraphic aspect of the fossils is decidedly Clinton. The several faunas from the argillaceous beds of the Pike Arm formation are essentially contemporaneous, and the assemblage of the Goldson conglomerates differs from that of the Pike Arm argillites only in containing *Pentamerus oblongus* and *Chonetes* n. sp. The echinoderm columnals in the Botwood sandstone have no correlative value. The *Stricklandinia* in the limestone blocks is of the same general time interval as the faunas of the Pike and Goldson formations, and similar to several specimens of *Stricklandinia* found in the coralline argillite of Burnt Island.

The closest correlatives of these Clinton strata should be sought in the Silurian areas nearest Newfoundland. These are on Anticosti and at Arisaig, Nova Scotia—the former in the Appalachian geosyncline, the latter in the Acadian. The Newfoundland faunas have only a few widely distributed species in common with the Arisaig assemblages. These are in the Ross Brook formation with which the Goldson and Pike Arm formations are correlated. The Botwood formation may correlate with the Beechhill formation. With three exceptions, every species identified from the Newfoundland Silurian is also present in the Jupiter formation of Anticosti. The three exceptions are new species of *Eophacops* and *Chonetes* and the *Stricklandinia* from the limestone blocks of Upper Black Island, and it may be that the latter fossil will ultimately be identified with one of the species of *Stricklandinia* from the Jupiter formation. It is concluded, therefore, that the Goldson and Pike Arm formations are of Jupiter age, and this correlation is clear and definite. The underlying Botwood formation may also be correlated with the Jupiter, or it may be equivalent to the Gun River or Becsie or parts of both of these. The close faunal relations of most of the Silurian sequence with the Jupiter proves that the strata were deposited in the Appalachian geosyncline rather than in the Acadian. On the other side of the Atlantic, the Goldson and Pike Arm formations are correlated with the Middle

and Upper Llandovery of the British section, with stages 6 and 7 of the Ringerike section of Norway as described by Kiaer, and with the *Stricklandinia* marl of the Gotland section.

PLEISTOCENE DEPOSITS

There is, in the region of Notre Dame Bay, positive and extensive evidence that the Pleistocene glaciers once covered that part of Newfoundland, and the same statement may be made for the area along the railroad to the Bay of Islands. In the last-named locality there is also evidence of glaciation everywhere except possibly on the highest peaks. Bare, barren, and abraded rock surfaces are common, and many have only a thin cover of vegetable matter. The surfaces everywhere suggest the passage of ice. Large boulders mantle the surface except where the materials represent outwash, or where the boulders have become covered by accumulations of vegetable matter. Many of the boulders are too high above sea level ever to have attained their positions by ice rafting, as for instance on the top of Limestone or Marble Mountain back of Corner Brook and on the top of the upland surface in the region of the "Topsails". Transportation by glaciers must be postulated.

There are extensive deposits of sorted gravel on Exploits River upstream from the estuary, on the upland surface to the west, and at numerous other localities around the Bay of Exploits. The elevations of many of these deposits, some of which are well shown along the road between Botwood and Bishop Falls, are too great to be interpreted as marine terraces. Every type of evidence forces the conclusion that they represent deposits made by the melt waters of glaciers. Moreover, the physiography of the deposits is of such nature as to preclude interpretation as marine terraces. Finally, the flat upland surface traversed by the railroad between Lewisporte and the Bay of Islands is essentially devoid of soil, and is more or less abundantly strewn with erratics. There are also gravel deposits on this upland with such characters that they can hardly be interpreted otherwise than as glacial till. Some of these deposits may be seen in railroad-cuts, whereas others nearby form characteristic hummocky topography. The freshness of the materials leads the writers to suggest that the glaciation correlates with the Wisconsin stage of the United States.

CONCLUSIONS

(1) The northeastward-trending belt, extending from Fogo Island and New World Island in Notre Dame Bay into the interior of Newfoundland as far as Grand Falls on the Exploits River, contains more than a mile of Silurian strata, which in order of abundance are sandstones (quartzites), conglomerates (conglomerites), and shales (argillites). These strata

are folded into a series of more or less overturned anticlines and synclines trending northeastward, with the axial planes inclined to the southeast. They are cut by reverse faults of considerable magnitude, which are inclined to the southeast, and by normal faults that seem of less magnitude.

(2) The Silurian sequence contains dikes and sills and was probably intruded by igneous bodies of batholithic proportions. These batholiths have not been seen in contact with Silurian strata, but they seem to be connected with the deformation that affected the Silurian.

(3) The order of deposition of the Silurian sedimentary sequence seems to have been as follows: sandstones, designated the Botwood formation; sandstones and conglomerates, constituting the Goldson formation; shales and sandstones, included in the Pike Arm formation; and limestones, which are of uncertain stratigraphic position. Rising lands seem necessary for the production of the clastics, especially the conglomerates.

(4) So far as known there is no angular stratigraphic relationship between the Ordovician and the Silurian systems. The structural relations between the Ordovician and the Silurian strata show no evidence of deformation at the close of the Ordovician. The great thickness of Silurian clastics, however, proves uplift of the source areas in late Ordovician or early Silurian time. The Silurian strata were deformed and metamorphosed after Clinton time. It is suggested that the deformation correlates with the Caledonian orogeny, but available evidence does not rule out the possibility that it may have been contemporaneous with the Acadian orogeny instead.

(5) The fossils collected are essentially contemporaneous and are correlative with the assemblage of the Jupiter formation of Anticosti. This formation, in turn, correlates with the Ross Brook of the Arisaig section, the Clinton of New York, and the Middle and Upper Llandovery of western Europe.

(6) The similarity of the faunas from the Goldson and Pike Arm formations of the Notre Dame Bay region of Newfoundland and the Jupiter formation of Anticosti proves that the Silurian of north-central Newfoundland was deposited in the Appalachian geosyncline.

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SILURIAN STRATA OF WHITE BAY, NEWFOUNDLAND

BY GEORGE R. HEYL

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INTRODUCTION

In the White Bay region, at the eastern base of the great Northern Peninsula of Newfoundland, Silurian rocks underlie a considerable area adjacent to the west coast of the bay.

The Northern Peninsula—the northward continuation of the Long Range Mountains—is an upland area of rugged topography; in the vicinity of White Bay it consists for the most part of pre-Cambrian crystalline rocks. Between this upland and the west shore of White Bay is a strip of country of lower altitude, underlain by Paleozoic rocks. This belt varies in width from 9 miles in its more southern portion to less than 3 miles at Coney Head near its north end. It consists of sedimentary rocks (with a relatively small proportion of volcanic rocks) which strike north-northeast, and, in general, dip to the east. The Paleozoic series is summarized in Table 1. The Silurian and older rocks are intruded by numerous felsic igneous bodies, large and small, including those of granite, quartz porphyry, quartz monzonite, and quartz diorite.

These Paleozoic rocks are best exposed along the shores of Jacksons Arm and Sops Arm (Fig. 1), two westward-extending inlets of White Bay which cross-cut the regional strike. One of the most complete sections of Paleozoic rocks in Newfoundland can be seen at Sops Arm.

The Silurian rocks of this region were first described by Murray,[1] who in 1864 studied the section in Jacksons Arm; he also visited Sops Arm and recorded his observations. Howley,[2] in 1902, made a general study of the rocks in White Bay and examined those in Jacksons Arm

TABLE 1.—*Paleozoic stratigraphy, west side of White Bay, Newfoundland*

Period	Sops Arm and Vicinity		Jacksons Arm	
	Formation	Thickness (Feet)	Formation	Thickness (Feet)
Mississippian	Spear Point formation	8,000±		
	Fault			
Silurian	Natlins Cove formation	10,700		
	Upper Sandstone member	2,325		
	Sops Island volcanic member	1,675	Natlins Cove formation	7,230
	Lower Sandstone member	6,700	Lower Sandstone member	7,230
			Fault	
Ordovician	Simms Ridge shale	2,340		
	Giles Cove formation	2,100±	Giles Cove formation	5,000±
	Jacksons Arm conglomerate member	0–400	Jacksons Arm conglomerate member	3,000±
	Deadmans Cove volcanic member	0–700	Deadmans Cove volcanic member	2,000±
	Taylors Pond shale member	1,000±	Taylors Pond shale member	
Cambrian	Doucers marble and limestone	120–300	Doucers marble and limestone	?
	Beaver Brook shale	910		
	Unconformity		Fault	
Pre-Cambrian	Hornblende gneiss and porphyritic granite gneiss		Porphyritic granite gneiss	

and Sops Arm. The results of the work of Murray and Howley in this region have been summarized recently by Schuchert and Dunbar.[3] In 1934, Snelgrove[4] investigated the gold deposits in the vicinity of Sops Arm, and, in conjunction with this, made observations concerning the stratigraphy.

ACKNOWLEDGMENTS

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[1] Alexander Murray: *Report for 1864*, Geol. Surv. Newfoundland (1881) p. 35-41.
[2] J. P. Howley: *Report for 1902*, Geol. Surv. Newfoundland (1918) p. 484-501.
[3] Charles Schuchert and C. O. Dunbar: *Stratigraphy of western Newfoundland*, Geol. Soc. Am., Mem. 1 (1934).
[4] A. K. Snelgrove: *Geology of gold deposits of Newfoundland*, Newfoundland Dept. Nat. Resources, Geol. Sect. Bull. 2 (1935) p. 38-40.

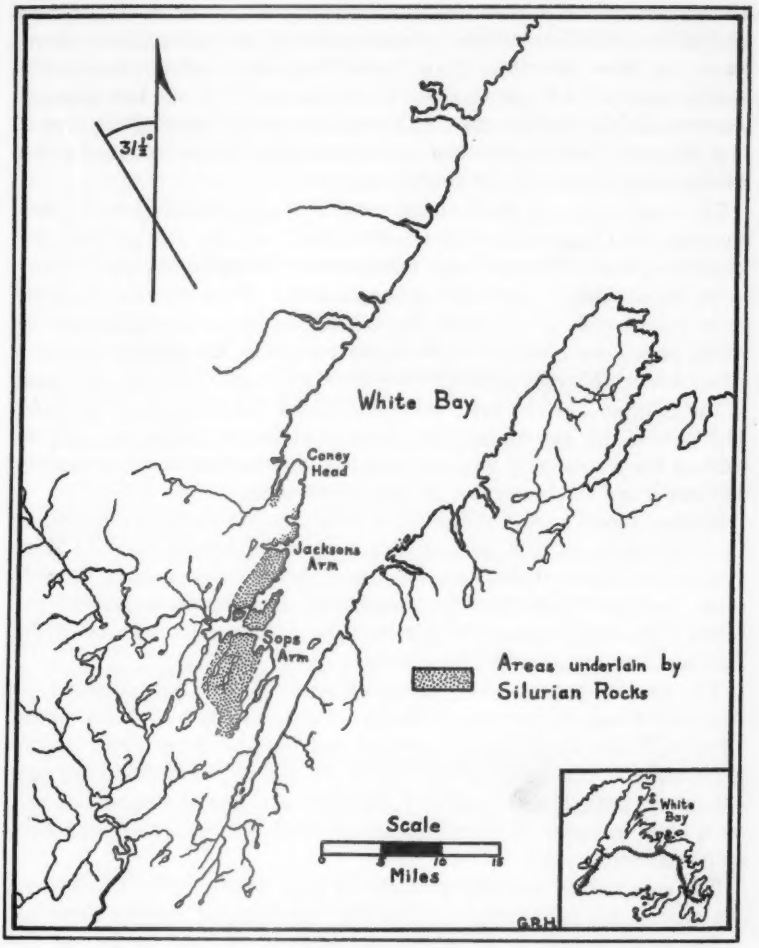

FIGURE 1.—*Areas underlain by Silurian rocks, White Bay, Newfoundland*

field, and have made constructive suggestions in the manuscript. Professor Twenhofel kindly identified the fossils.

SILURIAN SECTION AT SOPS ARM

The Silurian rocks at Sops Arm consist for the most part of fine-grained and argillaceous sandstone, with some siltstone near its base.

The succession has been named the Natlins Cove formation. The upper part of the formation includes a sequence of rhyolite and andesite flows, which has been called the Sops Island Volcanic member. Above this member occurs the Upper Sandstone member similar to the Lower Sandstone member of the formation. The eastern margin (top) of the formation is an inclined thrust fault of major proportions, separating the Silurian rocks from those of younger age.

The basal strata of the Silurian series are conformable in strike and dip with the Ordovician rocks beneath them, and the change from the underlying shales (Simms Ridge formation at the top of the Ordovician) to the basal siltstone and argillaceous sandstone of the Silurian is apparently gradational. Throughout the White Bay region no well-preserved fossils have been found in the formations beneath the Silurian, and the oldest fossils definitely identified are Silurian in age; therefore, the base of the Silurian has not been determined from paleontological evidence. The base of this system has been located where the shales give way to more or less consistently arenaceous strata; this horizon is approximately 400 feet below the lowermost Silurian fossil zone.

Silurian fossils have been collected at several places from the Natlins Cove formation on both sides of Sops Arm, including one zone (at West Point, Little Spear Cove) near the top of the formation, above the volcanic member. According to Twenhofel,[5] the general aspect of the fauna from these rocks is of Clinton age. The total thickness of the Natlins Cove formation at Sops Arm is 10,700 feet.

The Silurian is exposed on the south shore of Sops Arm almost continuously from the bottom of Baileys Cove eastward to Little Spear Cove, and also forms Georges Island and part of Sops Island on the north shore of the arm.[6] These rocks are cut by numerous dikes and sills of rhyolite, quartz porphyry, diabase, and quartz monzonite, and by a large intrusion of quartz porphyry which strikes across Sops Arm at its narrowest point.

The structure of the Silurian rocks in Sops Arm is fairly simple, and the general dip is eastward. Along the east shore of Baileys Cove are a few small reverse faults whose eastward dip is close to that of the bedding and whose displacement is practically negligible. Farther eastward, on both sides of the arm, are several minor faults of small displacement, some of which are definitely reverse in character. A fault of larger proportions is present in Spruce Cove where much of the movement has been horizontal, the eastern side moving northward.

The only folds exposed in this section are a small pair (anticline and syncline) near Little Spear Point and a larger synclinal drag fold asso-

[5] W. H. Twenhofel: personal communication.

[6] Detailed locations are shown on Sops Arm sheet, Map 6, Geological Survey of Newfoundland (1937).

ciated with the eastern boundary fault. Elsewhere the dip is eastward, its amount varying considerably. In the vicinity of the large porphyry intrusion, and near the larger faults, the dip is steeper.

A detailed stratigraphic section of the Silurian rocks in Sops Arm is given. This section is shown diagrammatically in Figure 2. The greater part of the section was measured along the south shore of the arm, but the upper part of the Lower Sandstone member and the lower part of the Volcanic member were measured on the north shore.

NATLINS COVE FORMATION, UPPER SANDSTONE MEMBER, SOPS ARM

Member	Description	Feet	
9.	Fine-grained gray sandstone, the lower portion including occasional calcareous beds, some of which contain irregular masses of calcite and poorly preserved fossils. The beds are considerably shattered and deformed, the topmost beds being at the center of a synclinal fold. Fossils collected: *Favosites gothlandicus, Clathrodictyon vesiculosum?*, crinoid stems. Zone F. (West Point, Little Spear Cove.)	425	2,325
8.	Fine-grained, medium-gray sandstone. An anticline and syncline of relatively small proportions cause a repetition of some of the beds here.	100	1,900
7.	Thin-, to medium-bedded, fine-grained, gray sandstone weathering pale gray, the lower portion containing some argillaceous zones; some of the beds show ripple marks. A 5-foot mafic dike cross-cuts these rocks	950	1,800
6.	Concealed	250	850
5.	Fine-grained gray sandstone. A 25-foot rhyolite dike is intruded into the uppermost portion of these beds. (Bottom, Big Spear Cove)	200	600
4.	Concealed	120	400
3.	Thin-bedded, fine-grained, slightly argillaceous gray sandstone	150	280
2.	Concealed	100	130
1.	Thin-bedded, fine-grained gray sandstone. A 25-foot fine-grained diorite dike cross-cuts these beds	30	30
	Total	...	2,325

NATLINS COVE FORMATION, SOPS ISLAND VOLCANIC MEMBER, SOPS ARM

Member	Description	Feet	
12.	Pale-yellow, and dark-gray rhyolite flows, some of them porphyritic and showing pronounced flow-banding. (West shore, Big Spear Cove) A 20-foot mafic dike is intruded into the lavas.	325	1,675
11.	Green-gray, chloritic andesite, with numerous calcite amygdules; also coarse andesitic breccia and dark-gray tuff	160	1,350
10.	Fine-grained, medium-gray sandstone	15	1,190
9.	Green-gray, chloritic andesite, much of it amygdaloidal. A rhyolite dike cross-cuts these lavas	500	1,175

Member	Description	Feet	
8.	Concealed; thickness unknown.		
7.	Gray-brown rhyolite, with pronounced flow-banding; tuffaceous rhyolite and some flow-breccia. Also medium-gray tuff, with occasional coarse fragments scattered through the beds; these rocks weather pale blue-gray. (East shore, Sops Island).....	175	675
	Small reverse fault of minor displacement.		
6.	Gray-brown rhyolitic tuff and breccia.....	90	500
	Small fault of minor displacement, following the margin of a sheared mafic dike.		
5.	Thin-bedded, pale green-gray tuff.....	10	410
4.	Coarse rhyolite breccia, containing fragments of banded rhyolite and of coarsely porphyritic rhyolite.....	30	400
3.	Gray-brown rhyolite with flow-banding (Birchy Point, Sops Island).	260	370
2.	Dark greenish-gray andesitic lava cut by innumerable fine quartz veinlets.....	10	110
1.	Gray-brown rhyolite, some zones showing faint banding.....	100	100
	Total.....	...	1,675

NATLINS COVE FORMATION, LOWER SANDSTONE MEMBER, SOPS ARM

Member	Description	Feet	
28.	Much shattered and slightly metamorphosed fine-grained sandstone, with some coarse-grained sandstone. Adjacent to the contact of a large quartz porphyry intrusion.....	25	6,700
27.	Concealed.....	85	6,675
26.	Fine-grained gray sandstone.....	20	6,590
25.	Pale-gray buff-weathering limestone.....	30	6,570
	Rhyolite dike, 20 feet thick.		
24.	Thin-bedded, fine-grained, medium-gray sandstone; several calcareous zones show pitted weathering and contain calcite nodules and poorly preserved fossils. Several small faults of minor displacement.	775	6,540
23.	Fine-grained, pale-gray calcareous sandstone with intercalations of thin-bedded sandstone. The calcareous beds frequently contain nodular masses of limestone and calcite, which upon weathering give the rock an irregular pitted appearance. Recognizable fossils occur in the more calcareous beds; they include the following forms: *Favosites hisingeri, F. gothlandicus, Clathrodictyon vesiculosum, Heliolites interstincta?, Cladopora?* sp., crinoid stems. Zone E. (Fossil Point, Sops Island).....	96	5,765
22.	Fine-grained, slightly argillaceous gray sandstone with occasional intercalations of calcareous sandstone.....	535	5,670
	Quartz monzonite dike, about 175 feet thick.		
21.	Even-bedded, fine- to medium-grained gray sandstone, much of it slightly argillaceous. Some of the upper beds show symmetrical ripple marks. These beds are intersected by a small reverse fault with a dip-slip of 2 feet.....	810	5,135
20.	Coarse arenaceous conglomerate, with intercalations of medium-grained sandstone, some of which show poorly developed cross-bedding. (East Point, Natlins Cove).....	110	4,325
	Quartz porphyry sill, 20 feet thick.		

19. Thin-bedded, fine-grained gray sandstone and argillaceous sandstone, the upper portion containing intercalations of coarse, poorly sorted grit and fine-grained arenaceous conglomerate. (Bottom, Natlins Cove)	865	4,215
18. Fine-grained gray sandstone with an occasional 1- to 2-foot bed of arenaceous limestone. Zone D (?)	265	3,350
17. Fine-grained gray sandstone with intercalations of shale and of coarse sandstone	730	3,085
16. Fine-grained gray sandstone, the uppermost 2 feet, calcareous sandstone	90	2,355
Reverse fault of minor displacement.		
15. Fine-grained gray sandstone	100	2,265
High-angle fault of considerable magnitude. (Bottom, Spruce Cove).		
14. Thin-bedded, fine-grained gray sandstone, the upper portion containing thin intercalations of pale-gray limestone, weathering buff and carrying small pyrite cubes; also some fine-grained arenaceous conglomerate	285	2,165
13. Fine-grained gray sandstone, weathering drab, with occasional argillaceous zones showing fracture cleavage. (Spruce Point)	420	1,880
12. Thin-bedded, laminated, gray argillaceous sandstone with several intercalations of white calcareous sandstone carrying fragments of fossils and crinoid stems. Zone C	115	1,460
11. Thin-bedded, gray, argillaceous sandstone, frequently showing fine laminations. In the lower portion there are several intercalations of calcareous sandstone carrying poorly preserved fossils including *Clathrodictyon vesiculosum?*. Zone B	740	1,345
A fault of minor displacement, with dip of fault plane very close to that of beds.		
10. Thin-bedded, light-gray siltstone with numerous intercalations of gray arenaceous shale	120	605
9. Pale blue-gray argillaceous limestone, weathering light brown	20	485
8. Thin-bedded, medium-gray, fine-grained argillaceous sandstone, weathering brown, with intercalations of light-gray arenaceous shale.	55	465
7. Poorly bedded calcareous shale. The upper 6 inches contains lenticular masses of calcite and the following fossils: *Clathrodictyon vesiculosum*, *Favosites gothlandicus?*, *Pentamerus?*, crinoid stems. Zone A. (East shore, Baileys Cove)	5	410
6. Irregularly bedded, light-gray argillaceous sandstone, weathering dull brown with irregular pits	120	405
5. Concealed	30	285
4. Fine-grained, light-gray argillaceous sandstone	65	255
3. Concealed	30	190
2. Thin-bedded, light-gray siltstone, weathering drab, with numerous intercalations of poorly bedded gray shale and less frequent intercalations of pale-gray, fine-grained sandstone	130	160
1. Medium-gray, finely arenaceous shale, weathering dull brown; the upper portion is somewhat calcareous. (Bottom, Baileys Cove)	30	30
Total	...	6,700
Total thickness of formation	...	10,700

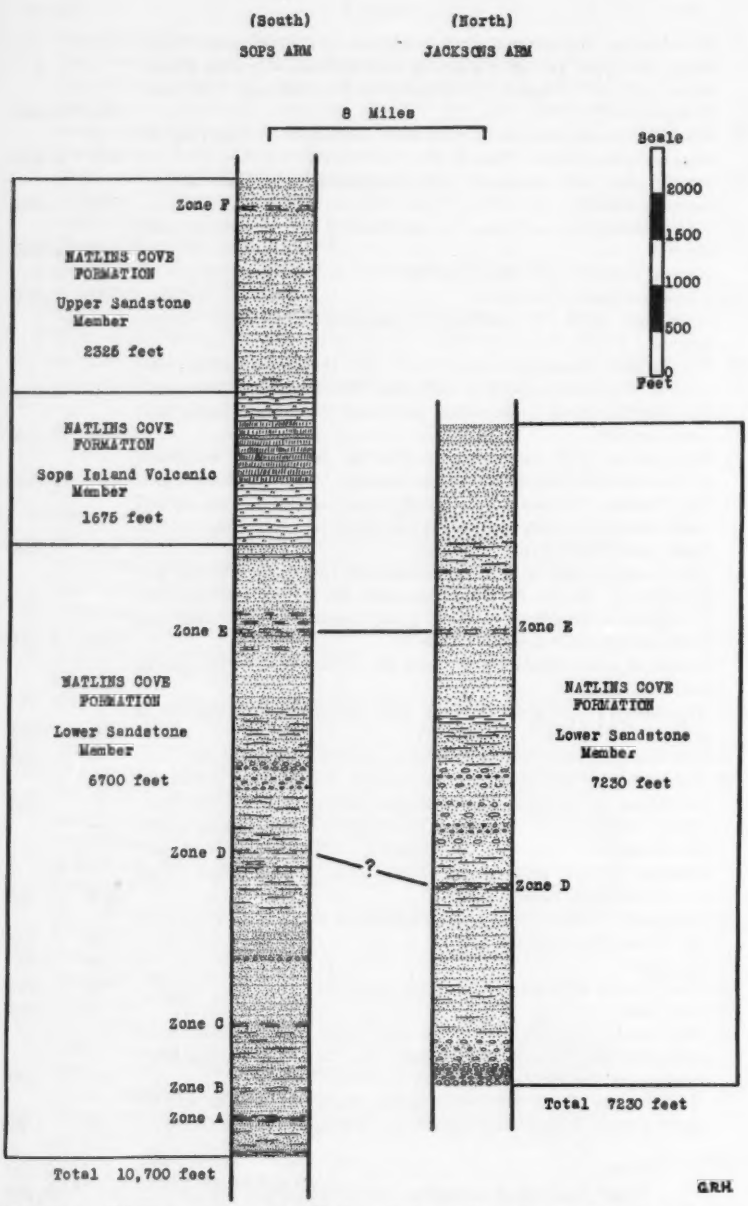

FIGURE 2.—*Columnar sections of Silurian strata at Sops Arm and Jacksons Arm, White Bay, Newfoundland*

SILURIAN SECTION AT JACKSONS ARM

The Silurian section at Jacksons Arm includes the greater portion of the Lower Sandstone member of the Natlins Cove formation. These rocks dip eastward at an angle varying from 85° to 50°. They are intruded by numerous dikes and sills of feldspar porphyry, quartz porphyry, and rhyolite. The total thickness of the Silurian strata exposed in Jacksons Arm is approximately 7230 feet.

In his study of the section at Jacksons Arm in 1864, Murray[7] included in the Silurian strata the coarse conglomerates and tuffaceous shales (Giles Cove formation, referred to the Ordovician) which outcrop near the bottom of the arm (Table 1). Since at Sops Arm these occur more than 2300 feet below the base of the Natlins Cove formation, with a distinctive series of shales and spotted shales (Simms Ridge formation, also referred to the Ordovician) intervening, the sequence at Jacksons Arm is abnormal. The Simms Ridge shale is not present at Jacksons Arm nor in the area west of it. The juxtaposition at Jacksons Arm of the Silurian rocks with the older conglomerates and tuffaceous shales is therefore almost certainly due to a fault. In West Clay Cove and in East Clay Cove, where the two formations are adjacent to each other, the physiographic evidence for a fault or fault zone along a line extending through these two coves is strong. Murray[8] placed a fault of major proportions at this point; he estimated the section of Silurian rocks at Jacksons Arm to be 2400 feet, if his figure of 400 feet for the thickness of the older coarse conglomerate and "mica schist" is subtracted. The discrepancy between the thickness as given by him and that given in this paper is a result of several factors. In the first place, Murray's section ends at Eastern Head on the north side of Jackson Arm; the measured section given in this paper continues as far eastward as Godfathers Point, about 3500 feet to the northeast. Murray says in referring to the top of his section that "the strong massive beds of quartzite . . . are supposed to belong to the summit of the section, but would give a much greater volume to this part of it than the amount stated." Secondly, Murray believed that two faults of major proportions (in addition to the one already mentioned) dislocated the Silurian strata and caused a threefold repetition of the beds; although several faults and crumpled zones are exposed in the Silurian rocks, none of these dislocations, except the fault zone crossing the arm at West and East Clay Coves, can be interpreted as causing any major displacement. Thirdly, the dips shown by Murray in his structure section of Jacksons Arm are much gentler than the actual dips of the strata; this difference in inter-

[7] Alexander Murray: *Report for 1864*, Geol. Surv. Newfoundland (1881) p. 35-37.
[8] *Ibid.*

pretation of the attitude of the rocks necessarily results in corresponding differences in the determined thicknesses.

In general, the similarity in the lithology of the Silurian rocks in Jacksons Arm with those at Sops Arm is quite marked. However, at Jacksons Arm conglomerate zones are more frequent, particularly in the

TABLE 2.—*Silurian fossils, Natlins Cove formation, White Bay, Newfoundland*

(Fossils identified by W. H. Twenhofel)

	Sops Arm, South Shore	Sops Arm, North Shore (Sops Island, Georges Island)	Grandmothers Point	Jacksons Arm
Upper Sandstone member	ZONE F *Favosites gothlandicus* *Clathrodictyon vesiculosum?* Crinoid stems			
Sops Island volcanic member				
Lower Sandstone member	ZONE C Crinoid stems ZONE B *Clathrodictyon vesiculosum?* ZONE A *Favosites gothlandicus?* *Clathrodictyon vesiculosum* *Pentamerus?* Crinoid stems	ZONE E *Favosites gothlandicus* *Favosites hisingeri* *Clathrodictyon vesiculosum* *Heliolites interstincta?* *Cladopora?* species Crinoid stems ZONE A *Favosites gothlandicus* Small brachiopods?	ZONE E *Favosites gothlandicus* *Clathrodictyon vesiculosum* *Heliolites interstincta?* Indeterminate "*Orthoceras*"	ZONE E *Clathrodictyon vesiculosum?* ZONE D *Clathrodictyon vesiculosum?*

lower and middle portions of the section, and calcareous zones are less common. Only one fossiliferous zone (Zone E) which could be definitely correlated with Sops Arm was observed in Jacksons Arm. This zone was also observed at intermediate localities, notably at Grandmothers Point on the mainland near the north end of Sops Island.

A detailed section of the Silurian rocks as exposed on the north shore of Jacksons Arm is as follows:

NATLINS COVE FORMATION, LOWER SANDSTONE MEMBER, JACKSONS ARM

Member	Description	Feet	
25.	Thin-bedded, fine-grained gray sandstone (Godfathers Point)	825	7,230
24.	Thick-bedded, coarse-grained, pale-gray sandstone, weathering white. Cross-bedding well developed. (Eastern Head)	450	6,405
23.	Fine-grained, slightly argillaceous gray sandstone	290	5,955
22.	Thin-bedded, fine-grained, buff, calcareous sandstone	30	5,665
21.	Thin-bedded, fine-grained gray sandstone. Cut by a 2-foot rhyolite dike	150	5,635
20.	Concealed (Bottom, Wicks Cove)	275	5,485
19.	Thin-bedded, fine-grained gray sandstone	190	5,210
18.	Moderately coarse-grained gray sandstone, with well-developed cross-bedding	30	5,020
17.	Gray calcareous sandstone, with nodular masses of calcite and poorly preserved corals: *Clathrodictyon vesiculosum?*. Zone E	3	4,990
16.	Thin-bedded, pale-gray calcareous sandstone, weathering buff. (West Point, Wicks Cove)	15	4,987
15.	Thin-bedded, fine-grained gray sandstone	900	4,972
14.	Medium-gray shale, and thin-bedded gray sandstone	275	4,072
13.	Thin-bedded, argillaceous gray sandstone Rhyolite sill, 10 feet thick.	310	3,797
12.	Thin-bedded, fine-grained sandstone with thin intercalations of fine-grained arenaceous conglomerate	190	3,487
11.	Thin-bedded, argillaceous gray sandstone. (Bottom, Schooner Cove)	110	3,297
10.	Medium- to fine-grained gray sandstone with numerous intercalations of arenaceous conglomerate. Cut by two 25-foot rhyolite dikes... Small fault.	525	3,187
9.	Fine-grained gray sandstone and argillaceous sandstone Small fault.	390	2,662
8.	Fine-grained, pale-gray calcareous sandstone Small vertical fault, movement horizontal.	75	2,272
7.	Fine-grained sandstone and calcareous sandstone with a 2-foot zone containing nodular masses of calcite and remnants of fossils, corals: *Clathrodictyon vesiculosum?*. Zone D (West Point, Schooner Cove).	12	2,197
6.	Fine-grained gray sandstone and argillaceous sandstone	300	2,185
5.	Fine-grained, slightly argillaceous gray sandstone. Cut by a 6-foot rhyolite dike	750	1,885
4.	Gray argillaceous sandstone and gray shale, weathering light gray..	250	1,135
3.	Fine-grained gray sandstone and argillaceous sandstone. Cut by a large felspar porphyry dike and a small rhyolite dike. (The Narrows)	350	885
2.	Thin-bedded, fine-grained gray sandstone with thin intercalations of fine-grained arenaceous conglomerate	290	535
1.	Medium- to fine-grained arenaceous conglomerate, with intercalations of fine-grained gray sandstone showing well-developed cross-bedding. Cut by a 5-foot rhyolite dike and a 20-foot rhyolite sill.. Fault. (East Clay Cove).	245	245
	Total	...	7,230

CORRELATION

The fossils collected from the Natlins Cove formation indicate a stratigraphic position in the older part of the Silurian. The same fossils are present in the Goldson and Pike formations of the Notre Dame region, and, moreover, the lithology of the fossiliferous and associated strata of the White Bay region, except for the conglomerates, is not greatly different from the lithology of the strata of the Notre Dame region. Twenhofel and Shrock[9] assign a Clinton age to the Notre Dame fossiliferous strata, and, since the deposition of the strata of both areas probably took place in the same body of water, it seems most reasonable to refer the White Bay fossiliferous strata to the Clinton.

EXTENT OF SILURIAN ROCKS IN WHITE BAY

The extent of the Silurian rocks in White Bay is unknown. It cannot be determined from Howley's [10] map of Newfoundland because the Ordovician as well as the Silurian rocks are included by him under the term "Silurian." The areas of Silurian rocks through a distance of at least 20 miles are shown in Figure 1, and they have been determined by the writer by detailed field work during the summer of 1936. The Silurian rocks are known to continue southward beyond the main area shown, but for what distance is not known. Northward from Jacksons Arm, the Natlins Cove formation outcrops along shore for about 2½ miles. Beyond this, as far as Coney Head, the coast consists almost entirely of intrusive rocks, mainly quartz diorite. On the west side of Coney Head, however, near the bottom of the cove, the Natlins Cove formation is again exposed, but its relation to the main area to the southward is undetermined.

Howley [11] considered the non-fossiliferous rocks along the southern part of the east shore of White Bay to be possibly Silurian in age. The rocks mapped [12] as Silurian on this shore are distinctly different in character from the Silurian strata on the west side of the bay. They are highly metamorphosed slates, mica schists, garnet schists, and tourmaline mica schists, which show little or no lithological resemblance to the Silurian of the west shore. Until these rocks have been studied much more thoroughly, and their structure and relationship with the adjacent rocks deciphered, it seems best not to include them among the Silurian rocks in this region.

---

[9] W. H. Twenhofel and R. R. Shrock: personal communication.
[10] J. P. Howley: *Geological map of Newfoundland* (1907, reprinted 1928) Westminster.
[11] J. P. Howley: *Report for 1902*, Geol. Surv. Newfoundland (1918) p. 496-497.
[12] J. P. Howley: *Geological map of Newfoundland* (1907, reprinted 1928) Westminster.

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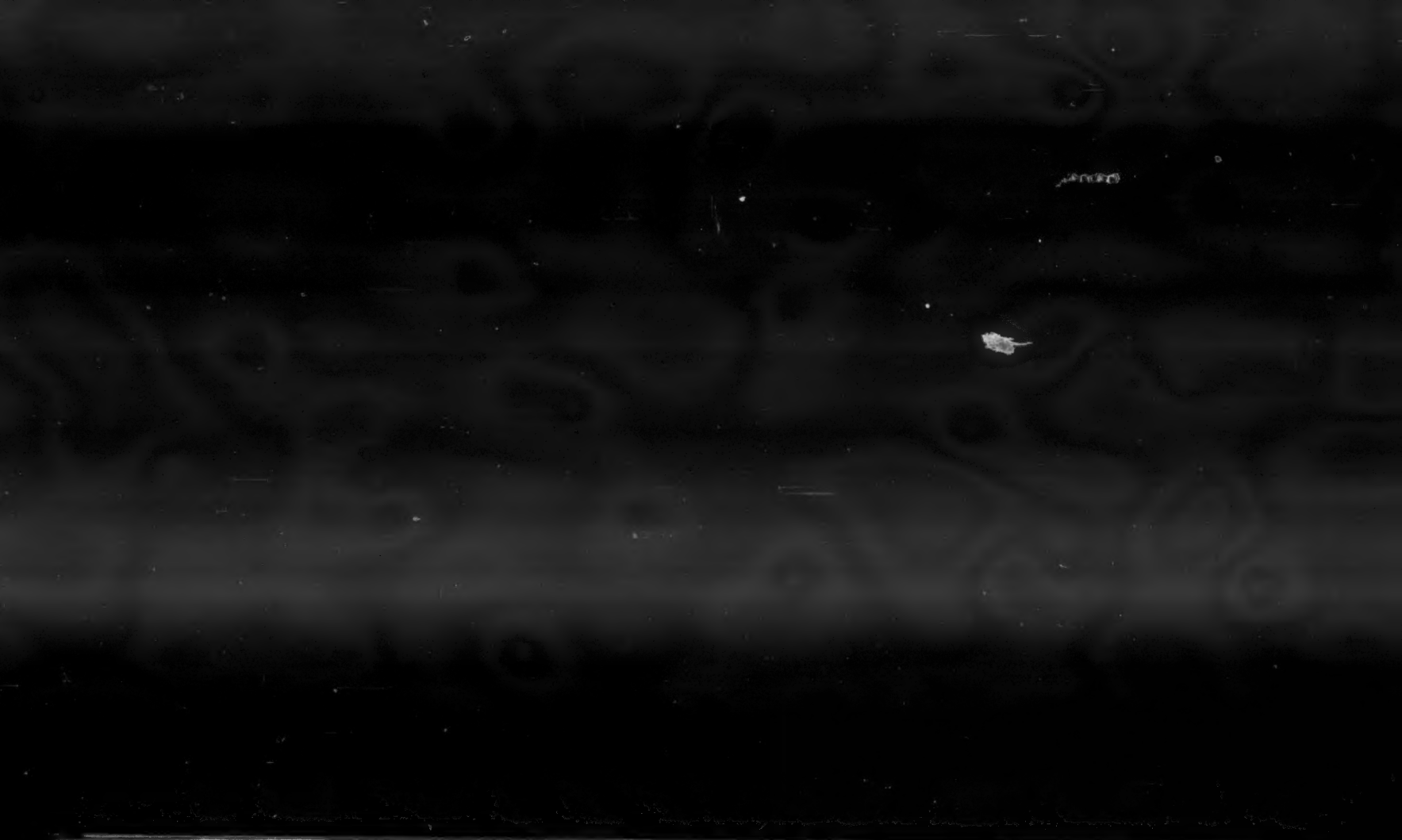


SECTION A-A'

SECTION B-B'

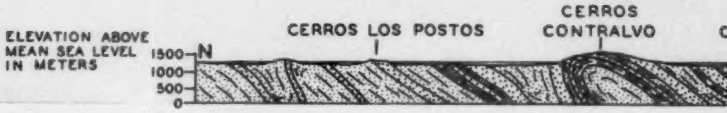
EXPLANATION

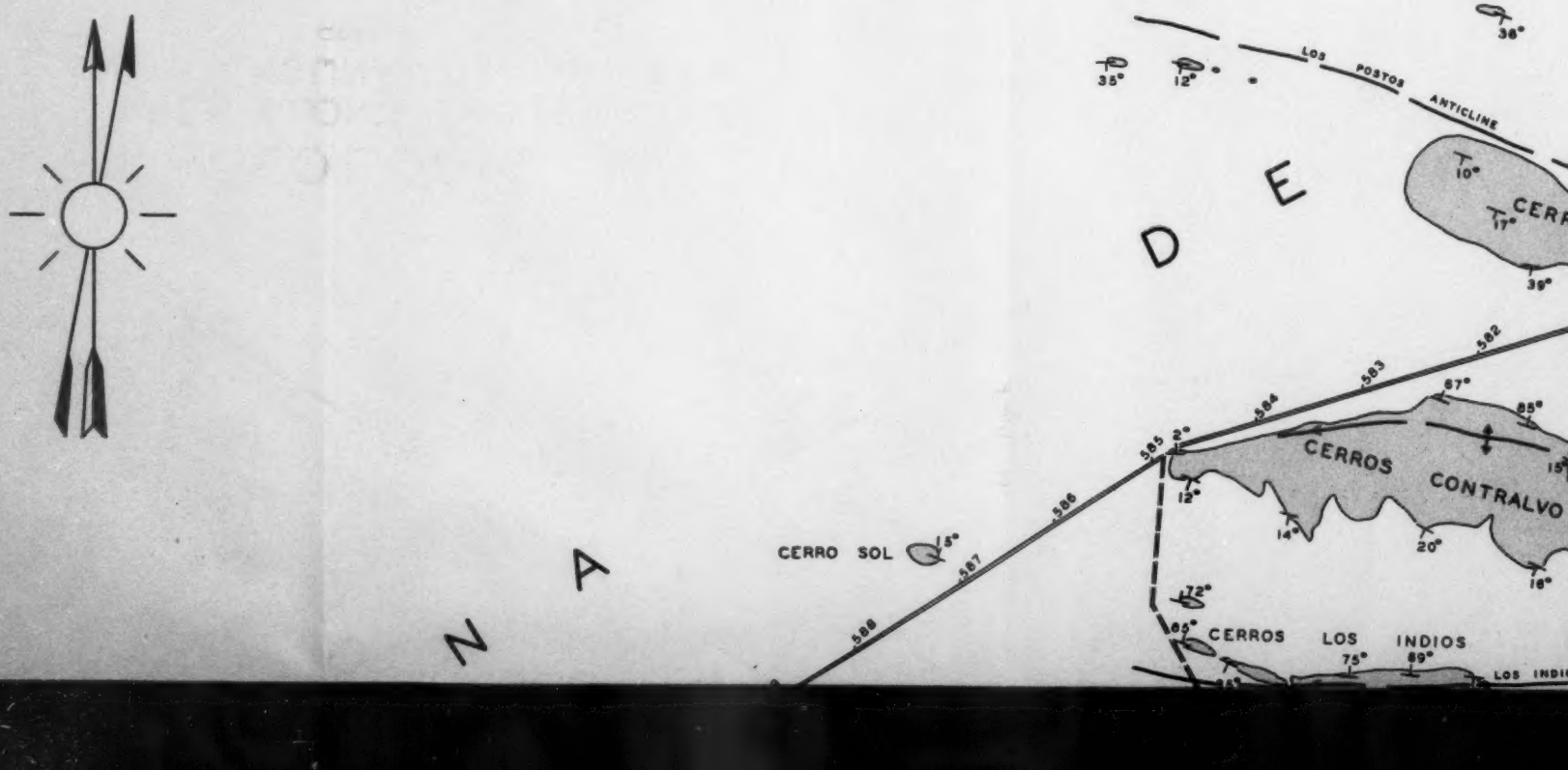
THICK-BEDDED SANDSTONE

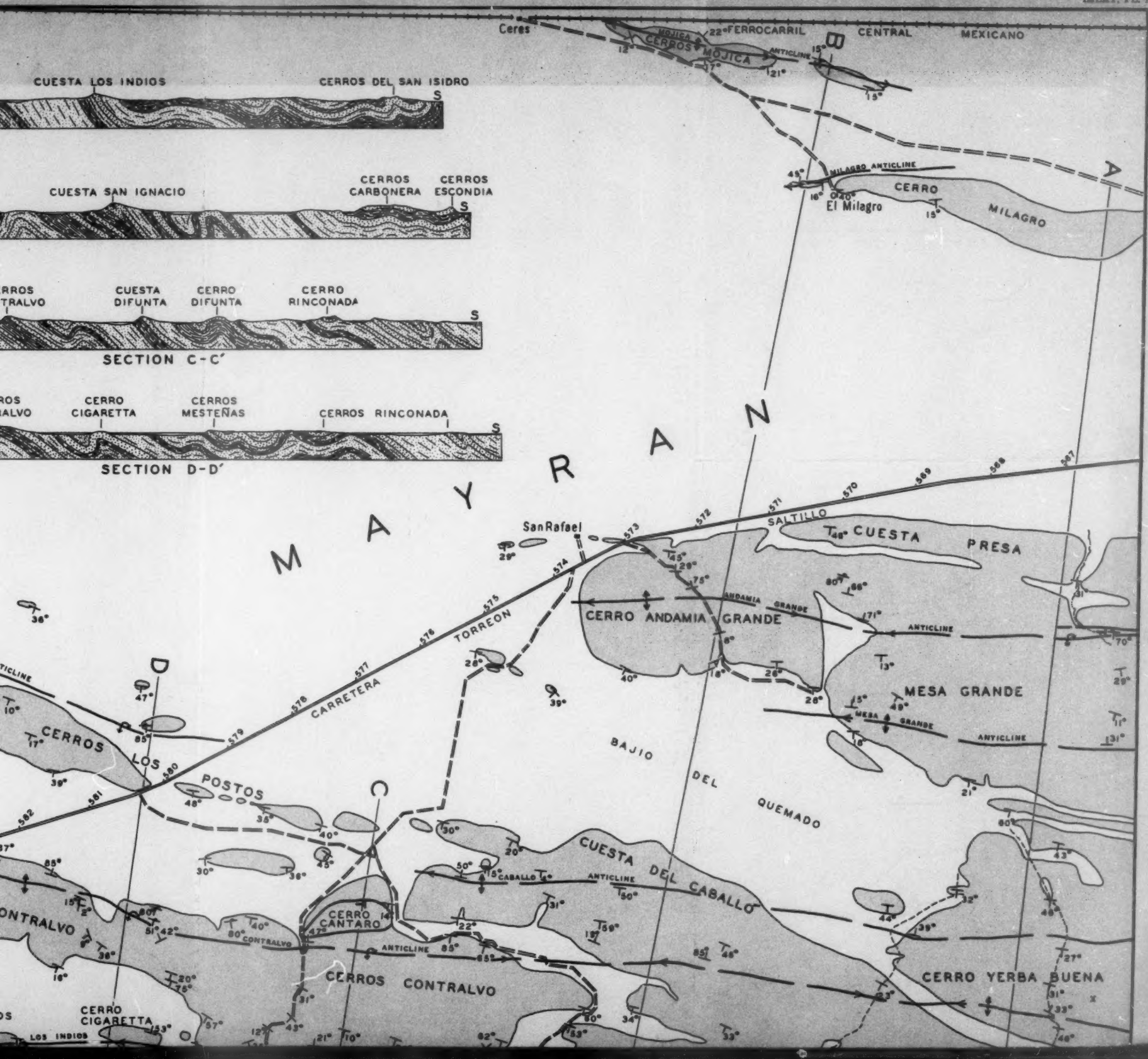
THIN-BEDDED OR SHALY SANDSTONE

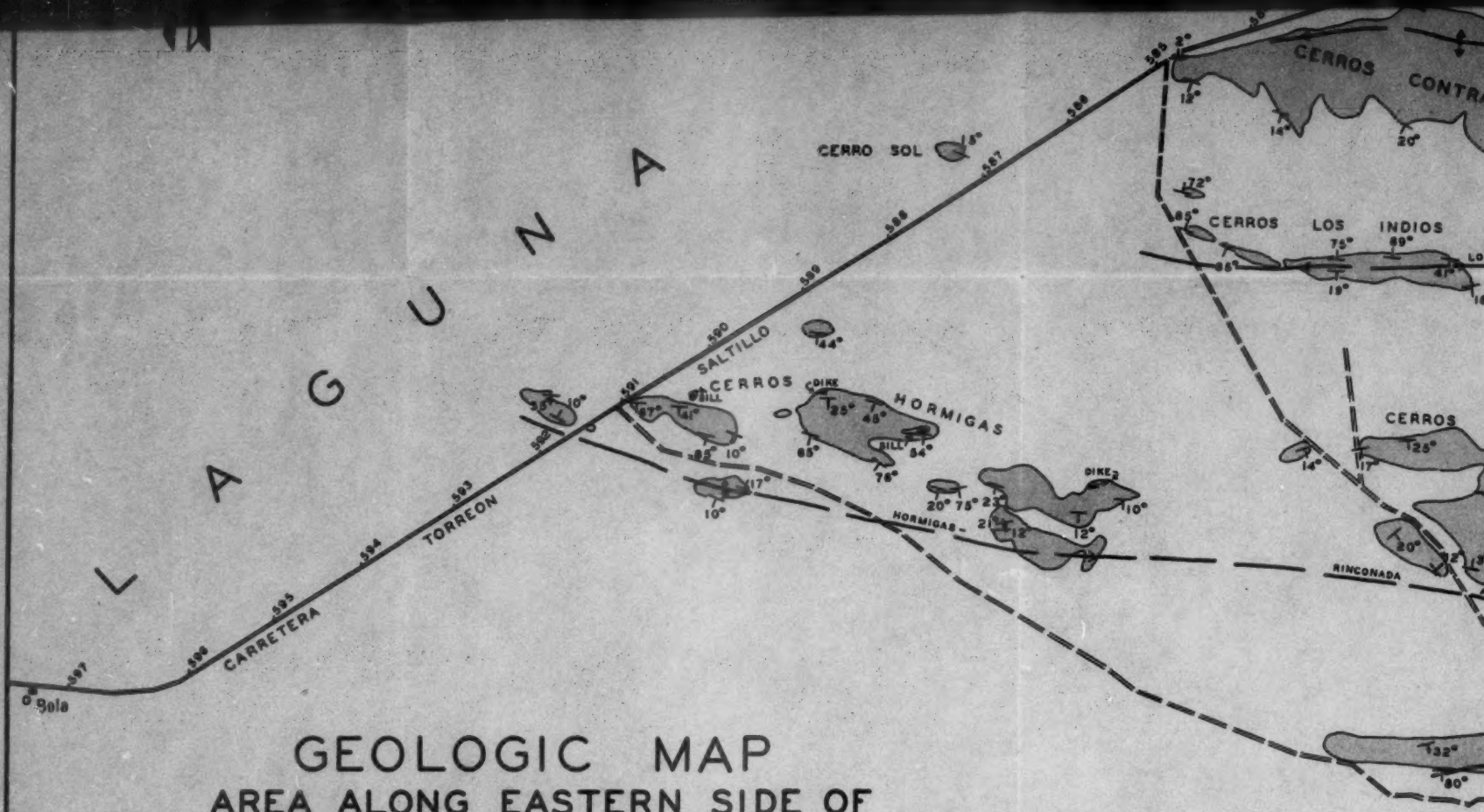
SHALES

NOTE: ALL SCALES IDENTICAL.






CUESTA LOS INDIOS
CERROS DEL SAN ISIDRO
CUESTA SAN IGNACIO
CERROS CARBONERA
CERROS ESCONDIA
CUESTA DIFUNTA
CERRO DIFUNTA
CERRO RINCONADA
SECTION C-C'
CERRO CIGARETTA
CERROS MESTEÑAS
CERROS RINCONADA
SECTION D-D'
MAYRAN
Ceres
FERROCARRIL CENTRAL MEXICANO
MOJICA
CERROS MOJICA
ANTICLINE
MILAGRO ANTICLINE
CERRO El Milagro
MILAGRO
SanRafael
SALTILLO
CUESTA PRESA
CERRO ANDAMIA GRANDE
MESA GRANDE
TORREON
CARRETERA
CERROS LOS POSTOS
BAJIO DEL QUEMADO
CUESTA DEL CABALLO
CERRO CANTARO
CERROS CONTRALVO
CERRO CIGARETTA
CERRO YERBA BUENA



GEOLOGIC MAP
AREA ALONG EASTERN SIDE OF LAGUNA DE MAYRAN
COAHUILA — MEXICO

BY R.W. IMLAY

0 1 2 3 4 5
KILOMETERS

0 1 2 3
MILES

LEGEND

SEDIMENTARY ROCKS

RECENT — ALLUVIUM

UPPER CRETACEOUS CAMPANIAN — DIFUNTA FORMATION

SYMBOLS

- AXIS OF ANTICLINE
- AXIS OF OVERTURNED ANTICLINE
- FAULT (BROKEN LINE PROBABLE FAULT — THRUST SIDE OF OVERTHRUST FAULT)
- FORMATION BOUNDARY
- 30° STRIKE AND DIP
- STRIKE OF VERTICAL STRATA
- 30° STRIKE AND DIP OF OVERTURNED STRATA

SIERRA DE LA P

GEOLOGIC MAP OF AREA ALONG EASTERN SID

EASTERN SIDE OF LAGUNA DE MAYRAN, COAHUILA, MEXICO

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 48, PP. 1785-1872, 26 PLS., 4 FIGS. DECEMBER 1, 1937

STRATIGRAPHY AND PALEONTOLOGY OF THE UPPER CRETACEOUS BEDS ALONG THE EASTERN SIDE OF LAGUNA DE MAYRAN, COAHUILA, MEXICO

BY RALPH W. IMLAY

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20. Fossils from the Difunta formation 1865
21. Fossils from the Difunta formation 1866
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INTRODUCTION

LOCATION AND EXTENT OF AREA

The area described in this report lies in southern Coahuila in the central part of the Parras Basin. It comprises about 175 square miles of hilly country, roughly triangular in outline, along the eastern side of the Laguna de Mayrán. The Central Mexican Railroad (Saltillo to Torreón) skirts

the northern border of the hills. Their western limit is approximately at a line drawn from the station of Ceres, on this railroad, southwest to Hacienda La Bola at the southern end of the Laguna de Mayrán. They are separated from the high ranges of the Sierra de Parras and Sierra de La

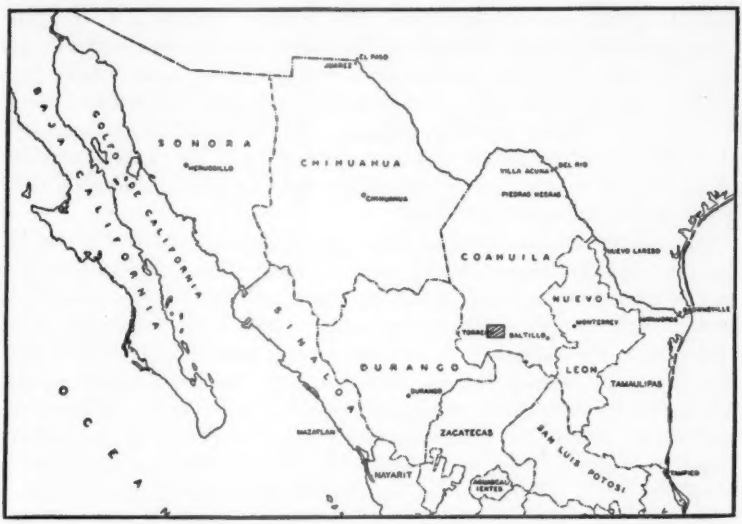

FIGURE 1.—*Index map of northern Mexico*

Peña on the south by a plain several miles wide and extend eastward parallel to the mountains for many miles. The area mapped will be referred to as El Pozo-Boquillas area, after the two principal settlements.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation and gratitude to the men who have made this work possible and who have taken an active interest in all its phases. Professor L. B. Kellum proposed the subject and has given assistance and encouragement both in the field and in the laboratory. Professor E. C. Case has given much good advice during the preparation of this work. Doctors L. W. Stephenson and J. B. Reeside personally examined the fossils and accorded the privilege of inspecting the Upper Cretaceous type specimens in the National Museum. Dr. Stephenson also read and commented upon the manuscript. The laboratory studies and preparation of this report were done in the Horace H. Rackham School of Graduate Studies of the University of Michigan.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

The hills of the El Pozo-Boquillas area [1] are of three types: namely, cuestas, rounded anticlinal hills, and hogbacks. These types are definitely related to the structures in the region. The cuestas mark the southern slopes of the anticlines. The rounded anticlinal hills occur rarely as small erosion remnants in the center of anticlinal highs (e. g., Cerro Difunta) or at the western ends of the anticlinal axes where they plunge beneath the alluvium of the Laguna (e. g., western end of Cerros Contralvo, Andamia Grande, Milagro, and Mojica). The hogbacks mark the sites of the overturned or vertical north flanks of the anticlines (e. g., western hills of Cerros Los Indios and the hills immediately east of Cerro La Cruz near Boquillas).

The cuestas face northward. The south slopes may be as high as 15 degrees, the north slopes as high as 45 degrees. The long south slopes range from a quarter to half a mile in length, are inclined at a somewhat gentler angle than the beds, and are steepest toward their summits. The escarpments are formed of thick-bedded sandstones ranging from a few feet to more than 50 feet in thickness, and interbedded with easily weathered, thin-bedded or shaly sandstones. As a result of differential weathering, most of the cliffs consist of a series of alternating long steep slopes, short gentle slopes, and benches. Sheer escarpments are uncommon.

All streams in this region are transient, flowing only during and for a few hours after a rain. The almost complete absence of grass permits rapid run-off and after a storm the arroyos become the beds of surging rivers.

The drainage from the northern hills of the El Pozo-Boquillas area is directly to the Laguna de Mayrán where the short steep arroyos disappear on the very edge of the plain. The southern hills are drained by Arroyo Difunta and its tributaries. Throughout its course the Arroyo Difunta follows synclines and saddles.

CULTURE

El Pozo and San Rafael are haciendas not exceeding 200 inhabitants each. San Ignacio is a small ranch with only two occupied houses. Boquillas and San Isidro are villages with populations not over 1000. Ceres is a railroad station. Bola is a mass of abandoned adobe ruins.

SEDIMENTARY ROCKS

The sedimentary rocks exposed east of the Laguna de Mayrán are entirely of Upper Cretaceous age. Along the south side of the Laguna a

[1] For regional setting *see* R. W. Imlay: *Geology of the western part of the Sierra de Parras*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 1095-1908.

thick series of Upper Jurassic and Lower Cretaceous limestones, shales, and sandstones are exposed in the Sierra de Parras and Sierra de La Peña. Lower Upper Cretaceous limestone and shale are present along the

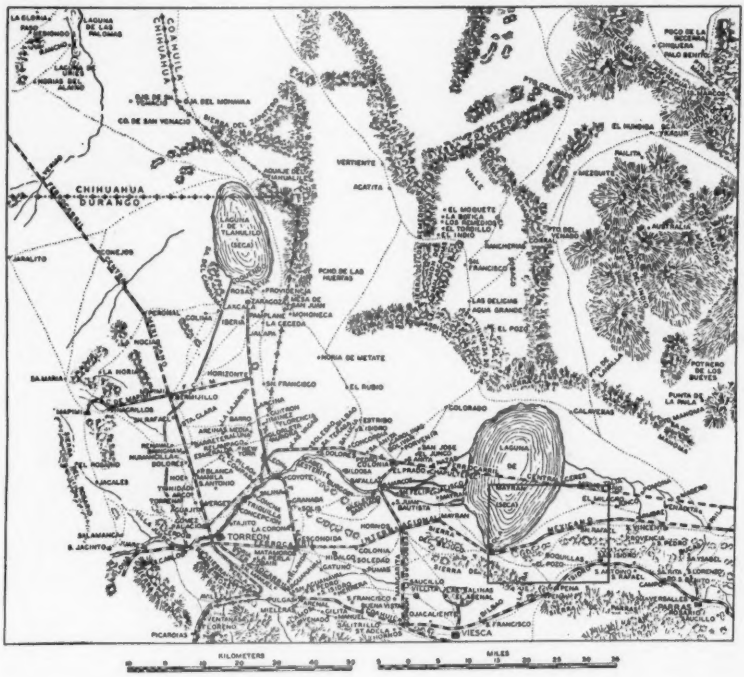

FIGURE 2.—*Physiographic map of southwestern Coahuila*

northern base of the sierras.[2] The beds of the Difunta formation exposed in the El Pozo-Boquillas hills all belong in the *Exogyra ponderosa* zone, which, according to Stephenson,[3] is equivalent to the upper Santonian and probably all the Campanian of Europe. These beds have an aggregate thickness of at least 12,000 feet and are probably much thicker. They consist of clastic sediments which are probably all marine but some are possibly of brackish water origin.

[2] For description of these beds see *op. cit.*, p. 1111-1133.

[3] L. W. Stephenson: *Correlation of the Upper Cretaceous or Gulf Series of the Gulf Coastal Plain.* Am. Jour. Sci., 5th ser., vol. 16 (1928) p. 492.

THE DIFUNTA FORMATION

LITHOLOGIC CHARACTERISTICS

The Difunta formation consists of conglomerates, thick-bedded sandstones, thin-bedded sandstones, shaly sandstones, and shales. All of them are highly calcareous. Shaly and thin-bedded sandstone predominate, although dark gray shales occur at many horizons. The dominant color on a fresh surface is gray, but red, brown, yellow, green, and black occur commonly.

Beds of conglomerates, as much as two feet in thickness, occur at short intervals throughout the section at or near the base of thick-bedded sandstone lenses. The pebbles are subangular and are almost exclusively limestone resembling the Lower Cretaceous limestones of the nearby mountains. The maximum diameter of the pebbles is about 2 inches but the average is about a quarter of an inch. The pebbles consist mainly of small calcite grains enclosing a few small, angular quartz grains and some limonite, probably derived from pyrite. The surfaces are coated with limonite. The matrix of the conglomerate consists of abundant calcite, a considerable quantity of angular quartz grains ranging from medium to small size, a little magnetite, and limonite.

Thick-bedded sandstones occur intercalated with thin-bedded and shaly sandstones. They range in thickness from a few feet to over 50 feet. They are lenticular, passing laterally into thin-bedded sandstones within short distances. The texture ranges from fine to coarse. Many beds overlie shaly sandstones with slight disconformity and some beds begin with a conglomerate whose pebbles are of limestone. Their upper surfaces are commonly marked by ripples of the current type (Pl. 4, figs. 2, 3). The color on a fresh surface is generally light gray but may be light yellow, deep yellow, brown, red, or green. The gray and brown, thick-bedded sandstones weather into large rectangular blocks whose surfaces are commonly covered with a glistening coat of dark brown iron oxide. The red, reddish brown, and green thick-bedded sandstones are hard and firmly cemented, but are less resistant to weathering than the gray and brown types. Most of the red and green types weather into peculiar thin splinters lying perpendicular to the bedding planes and terminating in long slender points which give a fuzzy appearance to the eroded upper surface of such beds.

In thin-section these sandstones are seen to consist mainly of quartz and calcite (Table 1). The calcite amounts to nearly 50 per cent in some specimens. In the field, the basal bed on Cerro Mojica appeared to be a sandstone, but microscopic examination showed it to be nearly two-thirds calcite. This was the only rock found in which the percentage of calcite exceeded that of the quartz. The quartz grains range from

small to large, and from subangular to sharply angular. The minor constituents include plagioclase as common grains, abundant magnetite, limonite, leucoxene, and glauconite.

Thin-bedded sandstones are much more common than thick-bedded sandstones but less so than the shaly sandstones. These lithologic types

TABLE 1.—*Qualitative microscopic examination of some sedimentary rocks from El Pozo-Boquillas area*

Rock	Constitutents						
	Quarts	Calcite	Plagioclase	Magnetite	Limonite	Leucoxene	Glauconite
1. Calcareous, arenaceous dark gray shale from plain about 3 miles south of Hacienda El Pozo	X	X	.....	X	X	.....	.....
2. Arenaceous limestone from basal bed on Cerro Mojica. Calcite forms about two-thirds of the rock	X	X	X	X	X	X	.....
3. Brown, calcareous sandstone from top of Cerros Contralvo near the eastern end	X	X	.....	X	X	.....	.....
4. Reddish brown, calcareous sandstone from Cerros Carbonera	X	X	X	X	X	X	X
5. Green, calcareous sandstone from Cerro Difunta	X	X	X	X	X	.....	.....
6. Brown, calcareous sandstone from a lens in black shales on the north slope of Cuesta Difunta	X	X	X	X	X	.....	.....
7. Grayish yellow, coarse-grained, calcareous sandstone from the south slope of Cerros Contralvo at fossil locality 20	X	X	.....	X	X	X	X
8. Light gray, fine-grained, calcareous sandstone from Cerro Mojica	X	X	X	X	.....	.....	.....
9. Conglomerate from a point a quarter of a mile north of Hacienda El Pozo. Pebbles are limestone	X	X	.....	X	X	.....	.....

grade into each other vertically and laterally. Thin layers of highly calcareous brown sandstone are also found in the dark gray or black shales where they rarely exceed 6 inches in thickness. Most of the thin-bedded sandstones occur in large stratigraphic units. They are moderately calcareous and the texture ranges from fine to coarse grain. The color is generally light gray on fresh surfaces but may be various shades of brown or yellow.

Calcareous shaly sandstones form the most common lithologic type in the section (Pl. 4, fig. 1). They grade laterally and vertically into shales and thin-bedded sandstones, or in places make rather sharp contacts with the shales. The fresh surface is some shade of gray, or rarely green, and the weathered surface light gray.

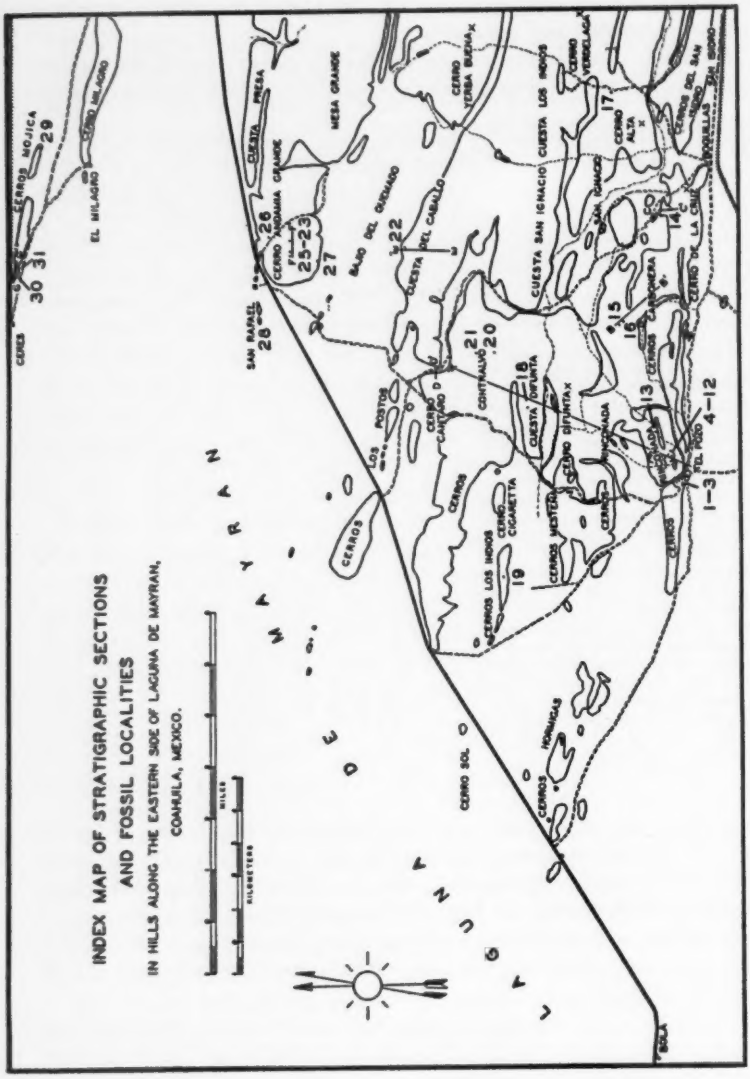

FIGURE 3.—*Index map of stratigraphic sections and fossil localities in El Pozo-Boquillas area*

Locally along the crests of anticlines where fracturing has been pronounced, the sandstones are characterized by an abundance of calcite. Some of the calcite veins contain numerous transparant quartz crystals which are seen on the surface throughout the area. Concerning the form and structure of these quartz crystals, George T. Faust, has kindly contributed the following note:

"The quartz crystals, ranging in size up to two and one-half centimeters in length, are very well developed and doubly terminated. The forms as seen under the hand lens consist of the prism m$(10\bar{1}0)$ in combination with the rhombohedrons r$(10\bar{1}1)$ and z$(01\bar{1}1)$. The forms r and z are in most specimens unequally developed. The trigonal pyramid s$(11\bar{2}1)$ occurs infrequently and may consist of only a very thin edge. Parallel growth is quite common and as usual is developed parallel to the c axis.

"The larger crystals usually have a rather pronounced skeletal development. The phenomenon is quite unusual and may indicate conditions of rapid growth. Many of the cavities in these skeletal crystals are filled with a clay-like material. The frequent occurrence of inclusions merits consideration. Most of the specimens show inclusions of a black solid and liquid bubbles are rather common. The very small, well developed crystals are however quite free of extraneous materials.

"The largest crystal found had both of its terminations broken off, and measured four centimeters along the prism face. It is probable that the crystal grew unattached, and if so its original length was about seven or eight centimeters."

Calcareous shales ranging from a few feet to several hundred feet in thickness occur at many places. At some places they grade vertically into shaly sandstones, at others they have a sharp contact. They are usually poorly exposed in long, narrow, east-west strips which extend continuously across the area. The color is commonly dark gray, but black, red, and green shales also occur as fairly persistent layers intercalated with dark gray shales or in distinct beds between sandstone lenses. Most red and green shales are associated with gray, shaly sandstones. The contacts of the various colored shales may be sharp or gradational. Along the walls of Arroyo Difunta, north of Cerro Difunta, nearly vertical beds of red, black, and green shales are intercalated with red, gray, and green sandstones. In one strip about 20 feet wide there are five layers of shale of different color which alternate and have sharp contacts between them, or with fragments of one color in the basal few inches of the overlying shale of another color. The dark gray and black shales are very soft and generally nodular.

As the regional dip is strongly southward, the oldest beds of the Difunta formation are exposed in Cerros Mojica near Ceres and the youngest beds near El Pozo and Boquillas. The measured sections, whose position is shown in Figure 3 and stratigraphic relationships in Figure 4, will be described from top to bottom. The descriptions are considerably summarized.

SECTION A-A'

Unit	Feet
1. Shale, fissile, black, with lenses of fine-grained yellow sandstone up to 6 inches thick which are more common toward the top	325
2. Sandstone, thin-bedded, fine-grained, gray	12
3. Shale and shaly sandstone, gray	45
4. Sandstone, thick-bedded, gray	10
5. Shale, fissile, dark gray	35
6. Sandstone, thin-bedded with 16 inches of conglomerate at base	18
7. Shale, dark gray	20
8. Shale, sandy, gray. Collection 1 from middle; collection 2 made 5 feet from base	33
9. Sandstone, thick-bedded, gray	10
10. Sandstone, shaly. Collection 3 at base	30
11. Sandstone, thick-bedded, gray	10
12. Sandstone, shaly, poorly exposed. Compact sandstone lenses up to 6 inches thick occur every 5 to 10 feet. Collection 5 at base	88
13. Sandstone, thick-bedded, compact, light gray	33
14. Chiefly shaly sandstones with some lenses of thin- or thick-bedded sandstones ranging from 6 to 14 inches in thickness. Sandstones are gray on fresh surface. The thick-bedded sandstones weather gray to brown, the shaly sandstones from gray to buff. The thick-bedded sandstones commonly overlie the shaly sandstones with slight disconformity as shown by irregular bottom surfaces, or by thin beds of conglomerate at their bases. The pebbles of the conglomerates are mainly of limestone and rarely exceed half an inch in size. Ripple marks of the current type are common on the surfaces of the thin- and thick-bedded sandstones. Plant impressions are abundant in the coarser sandstones. Fossil collections 6 to 12 were obtained from the upper 200 feet of this unit which is the most fossiliferous part of the entire section, containing species similar to those in the San Miguel formation of Texas	1400
15. Shale, fissile, black	165
16. Sandstone, shaly to thin-bedded, with a few lenses of gray, thick-bedded sandstone near middle of unit	580
17. Shale, fissile to papery, black, including lenses of sandstone as much as one foot thick	110
18. Sandstone, shaly to thin-bedded, gray	390
19. Shale, fissile, greenish black	48
20. Sandstone, thin-bedded, gray	240
21. Sandstone, thick-bedded, light gray, locally contains palm leaves	31
22. Shale and sandstone, red, with two 5-foot beds of gray sandstone near base	121
23. Shale, fissile, greenish black	34
24. Shale and sandstone, red	17
25. Sandstone, thin- to thick-bedded, light gray	83
26. Shale, sandy, grayish yellow	38
27. Sandstone, thick-bedded, gray	10
28. Sandstone, shaly, light gray	52
29. Sandstone, gray and red, including some black shales in middle of unit	20
30. Sandstone, platey, light yellowish gray	13
31. Sandstone, red	10

Unit	Feet
32. Sandstone, shaly to thin-bedded, gray; lenses of gray or brown, thick-bedded sandstone up to 20 feet thick fairly common in lower 700 feet. Fossil collection 18 made about 300 feet from base of unit	1225
33. Shale, nodular to fissile, black, with some lenses of yellow sandstone up to 4 feet thick	480
34. Sandstone, thin-bedded to shaly, with two 5-foot lenses of thick-bedded sandstone near the middle	430
35. Sandstone, shaly, red	17
36. Shale, greenish black	17
37. Sandstone, shaly and thin-bedded, with 12 lenses of thick-bedded sandstone ranging from 1½ to 5 feet in thickness. Collections 20 and 21 are 110 feet and 30 feet respectively above base	236
38. Sandstone, gray, thin-bedded mainly, but with many lenses of thick-bedded sandstone ranging from 4 to 20 feet in thickness	132
39. Sandstone, gray, thin-bedded at top, becomes shaly toward base	160
40. Shale, dark gray	81
41. Sandstone, thin-bedded to shaly, gray	58
42. Shale, light yellow	31
43. Sandstone, shaly, with two thin beds of compact sandstone near top	96
44. Shale, black, poorly exposed	100
Total	7084±

SECTION B-B'

Unit	Feet
1. Sandstone, thick-bedded, medium gray	2½
2. Sandstone, shaly, light gray, plant traces	5
3. Shale, green and red, with 3 feet of sandstone near top	38
4. Sandstone, thick-bedded, brown to gray	18
5. Shale, green at top grading into red below	49
6. Sandstone, brownish gray	10
7. Sandstone, shaly, gray	20
8. Sandstone, thick-bedded, brownish gray	4
9. Sandstone, shaly, reddish brown	4
10. Shale, red	50
11. Sandstone, reddish brown	3
12. Shale, red	30
13. Sandstone, thin-bedded, light gray	6
14. Shale, red	39
15. Sandstone, shaly to thick-bedded, light gray	64
16. Sandstone, shaly, red	38
17. Sandstone, thick-bedded, dark gray	10
18. Shale and sandstone, red	52
19. Sandstone, thick-bedded, light gray	5
20. Shale, fissile, dark gray	35
21. Sandstone, thick-bedded, gray	8
22. Shale, black	20
23. Sandstone, thick-bedded, dark yellowish gray	15
24. Sandstone, shaly, gray, collection 16 from upper 7 feet	137
25. Sandstone, shaly to thick-bedded, gray	99
26. Sandstone, shaly, gray	100

Unit	Feet
27. Sandstone, platey, hard, dark gray, contains *Ostrea sigmoidea* in abundance	34
28. Sandstone, shaly, gray	142
Total	1038±

SECTION C-C'

Unit	Feet
1. Shale, dark gray, with three 1-foot lenses of hard sandstone in upper 8 feet. Well-preserved *Exogyras* at top of shale	47
2. Sandstone, shaly, gray contains many molds of pelecypods and gastropods	93
3. Shale, sandy, gray. Collection 14	30
4. Sandstone, shaly, light yellowish gray	50
5. Sandstone, thick-bedded, light gray	5
6. Sandstone, shaly, gray, with several thin lenses of compact sandstone	63
7. Sandstone, shaly, red	28
8. Sandstone, shaly to thin-bedded, gray	7
9. Sandstone, shaly, red	5
10. Sandstone, thick-bedded, gray	61
11. Sandstone, thin-bedded, gray	56
12. Sandstone, thick-bedded, light gray	31
13. Sandstone, red	8
Total	484

SECTION D-D'

Unit	Feet
1. Shale, red and black	20
2. Sandstone, light yellowish gray, alternating shaly, thin-bedded, and thick-bedded; some beds gradational	118
3. Shale, gray, with sandstone lenses	18
4. Sandstone, light gray, to yellowish gray, alternating shaly and thick-bedded	90
Total	246

SECTION E-E'

Unit	Feet
1. Sandstone, alternating shaly and thick-bedded, beds rarely gradational, gray to light brown	121
2. Shale, light gray, with sandstone lenses	38
3. Sandstone, thick-bedded, yellowish gray	16
4. Shale, gray, with lenses of compact brown sandstone up to 6 inches thick	44
5. Sandstone, compact, gray	3
6. Shale, light gray, with thin lenses of compact, light brown sandstone	43
7. Sandstone, compact, grayish yellow	3½
8. Shale, dark gray	46
9. Sandstone, alternating shaly and thick-bedded, gray to brown	51
10. Shale, fissile, dark gray	20
11. Sandstone, thick-bedded, light gray	12
12. Sandstone, shaly, gray	9
13. Shale, dark gray	85
14. Sandstone, shaly, gray	89
15. Shale, dark gray	70
16. Sandstone, thin-bedded to shaly, with some thick beds of compact sandstone, gray	324

Unit	Feet
17. Shale, dark gray with lenses of yellowish brown sandstone up to 16 inches thick	48
18. Sandstone, thin-bedded to shaly, gray	128
19. Shale, dark gray, with thin beds of brown sandstone	170
20. Sandstone, thin-bedded to shaly, gray	190
21. Shale, light gray, with thin beds of yellowish brown sandstone	38
22. Sandstone, shaly to thin-bedded, gray to yellowish gray, Collection 22 made 60 feet above base	337
23. Sandstone, shaly, with many thin beds of grayish yellow sandstone containing *Ostrea saltillensis* Böse and *Lima coahuilensis* Böse	75
24. Shale, gray, with thin beds of yellow sandstone	20
25. Sandstone, thin- to thick-bedded, light brown	14
26. Sandstone, shaly, gray	25
Total	2020±

SECTION F-F'

Unit	Feet
1. Sandstone, thick-bedded, light gray	31
2. Sandstone, shaly, gray	90
3. Shale, dark gray, with beds of brown sandstone not over 2 inches thick	51
4. Sandstone, shaly. Shalier toward top	50
5. Sandstone, compact, gray. Collection 24	2
6. Shale and shaly sandstone, light gray	61
7. Sandstone, thick-bedded, light gray	4
8. Shale, nodular, dark gray	12
9. Sandstone, shaly, gray	18
10. Shale, nodular to fissile, dark gray	85
11. Sandstone, thick-bedded, gray	6
12. Shale, nodular to fissile, dark gray	33
13. Sandstone, thin-bedded to shaly, gray, collection 23 at top	19
14. Shale, dark gray, with thin beds of sandstone	17
15. Sandstone, thick-bedded, gray	11
16. Shale, dark gray	43
17. Sandstone, shaly to thin-bedded, gray	36
18. Shale, black	40
19. Shale and shaly sandstone of undetermined thickness.	
Total	609+

SECTION G-G'

Unit	Feet
1. Sandstone, thick-bedded, light gray	6
2. Shale, sandy, yellowish green	12
3. Sandstone, thick-bedded, light gray, with a shale lens	12½
4. Shale, yellowish green, with sandstone lenses	12
5. Sandstone, thick-bedded, light green	8
6. Shale, nodular, black, with thin sandstone beds	10
7. Sandstone, thick-bedded, dark gray	22
8. Shale, yellowish green, thin beds of brown sandstone	9
9. Sandstone, thick-bedded, light brown	8
10. Shale, nodular, gray. Collection 30 at base	22
11. Sandstone, thick-bedded, light brown, with 6 inches of shale at base	10
12. Limestone, thick-bedded, sandy, gray. Collection 31	12
Total	144

SOURCE OF SEDIMENTS

The presence of abundant magnetite and plagioclase grains throughout the great thickness of the Difunta formation suggests that the source of these sands was probably a body of igneous rock. The angular to subangular shape of the quartz grains in the sandstones and the subangular shape of the limestone pebbles in the conglomerates may imply that their source was not very distant. However, the fact that the pebbles in the conglomerates are almost exclusively limestone suggests either that the source of the quartz was more distant from the basin of deposition than the source of the limestone, or that the rocks containing the quartz were loosely consolidated. The former possibility is more probable in this case.

There are no known source rocks to explain the quartz in the regions north, east, or southeast of the Parras Basin. These regions are underlain by a thick series of Lower Cretaceous limestones and shales through which Jurassic or older rocks locally outcrop. The pre-Cretaceous formations are a possible source of the quartz but in these three regions the exposures are limited and were made during the Tertiary.

Possible sources for the quartz are believed to lie west or south of the Parras Basin. Several igneous intrusives in the Lower Cretaceous limestones are known north and west of Torreón. Perhaps others are now concealed by the alluvium of the bolsons. Practically nothing is known concerning the regions south and west of the Sierra de Jimulco. Böse and Cavins said:

> "It is very possible that a continent stretched through western Chihuahua, Durango, and Zacatecas during the time from the Turonian to the upper Santonian and it may have existed also on the west coast of Mexico at least in the northern part."[4]

Such a land area during upper Santonian and Campanian time probably furnished the great thickness of sediments in the Parras Basin. Wherever the source may have been, it was not distant from the Parras Basin of deposition but was separated from it by lands exposing Lower Cretaceous limestones. The latter fact is shown by the present extensive distribution and great thickness of these limestones in all the mountain ranges surrounding the Parras Basin and by the almost exclusive presence of limestone pebbles in the conglomerates of the Difunta formation. Early stages of the mountain ranges may have formed a fringe of islands around the sea which occupied the Parras Basin in Upper Cretaceous time, or they may have formed part of the mainland on which extensive areas of igneous rocks or of clastic sedimentary rocks were undergoing active erosion.

[4] Emil Böse and O. A. Cavins: *The Cretaceous and Tertiary of southern Texas and northern Mexico*, Texas Univ., Bull., vol. 2748 (1927) p. 101.

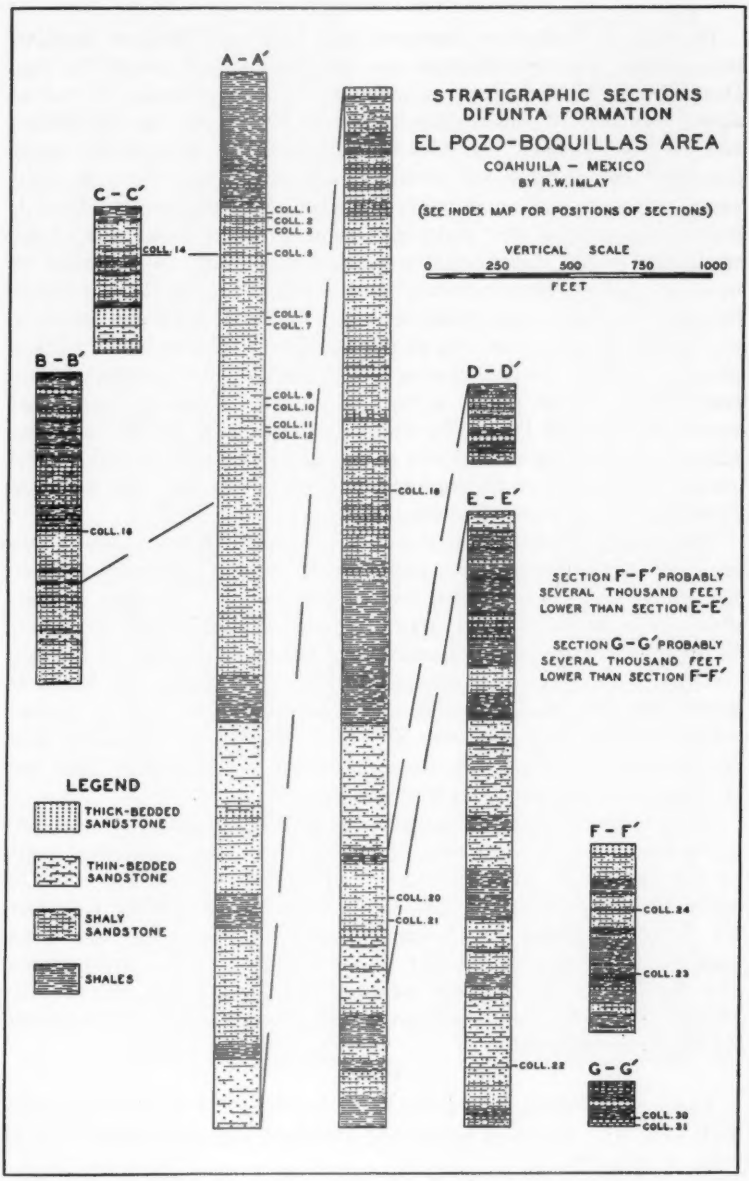

FIGURE 4.—*Stratigraphic sections of the Difunta formation*

DEPOSITION IN A SUBSIDING TROUGH

The Difunta formation represents both near- and off-shore shallow-water facies, but becomes more and more arenaceous toward the top. Deposition in shallow water is indicated by the occurrence of *Ostrea sigmoidea* Imlay in considerable abundance throughout the thin-bedded and shaly sandstones. The thick-bedded sandstones show shallow water deposition in several ways: First, in many places they lie with slight unconformity upon the underlying shales and shaly sandstones. In some places, fragments of the shales are included in the basal part of the sandstone. Slight disconformities such as these might be produced by wave or current scour previous to the deposition of the sandstone. Second, thin beds of conglomerate ranging up to 16 inches in thickness are fairly common at the base of thick-bedded sandstone lenses. Third, plant impressions are abundant in certain beds. These represent mainly small stems. A few pieces of wood as much as a foot in length were found on Cerro El Pozo. On Cerro Difunta an excellently preserved impression of a large portion of a palm leaf was found in a thick-bedded sandstone. Fourth, ripple marks, usually of the current type, mark the upper surfaces of many sandstone beds.

The absence of beds younger than Turonian in the Sierra Madre Oriental east of the Parras Basin indicates that little, if any younger Upper Cretaceous was ever deposited there. If beds of Senonian age comparable with those in the Parras Basin had been deposited, then somewhere in the narrow folds of the Sierra Madre Oriental there should be some trace of beds above the Turonian. On the south side of the Sierra de Parras the Turonian is overlain by sandstones and sandy shales[5] which represent only the lower Senonian. The Upper Cretaceous beds in northeastern Mexico total about 3500 feet of which about 1200 feet is Campanian, judging from Böse's estimates.[6]

The absence of deposits equivalent to the Difunta formation east and southeast of the Parras Basin, their absence or small thickness south of the basin, their great thickness within the basin compared with the much smaller thickness of beds of similar facies in northern Coahuila, all show that during the Campanian time the Parras synclinal basin sank at a much greater rate than the surrounding regions. Furthermore, the character of the deposits indicates that the sea was always quite shallow, and, therefore, the sediments accumulated at about the same rate as subsidence occurred.

FOSSILS

Localities.—Fossils were found at 31 localities[7] in El Pozo-Boquillas hills (Fig. 3). The most varied and abundant collections were made at

[5] *Op. cit.*, p. 76.
[6] *Op. cit.*, p. 28-56.
[7] Collection and locality numbers are the same.

FIGURE 1. EL POZO-BOQUILLAS HILLS AND SIERRA DE PARRAS
View south from Cuesta Difunta. Arroyo Difunta in foreground.

FIGURE 2. EL POZO-BOQUILLAS HILLS AND SIERRA DE LA PENA
View southwest from Cuesta Difunta (continuation of Figure 1).

FIGURE 1. SOUTH FLANK OF THE DIFUNTA ANTICLINE
View eastward from Cerro El Pozo

FIGURE 2. CREST OF DIFUNTA ANTICLINE
View eastward. Cerro Difunta (center), Cuesta Difunta (left).

FIGURE 3. CREST OF DIFUNTA ANTICLINE
View westward from Cerro Difunta. Cerros los Indios in distant middle right.

DIFUNTA ANTICLINE

localities 5 and 14. The large gastropods of the genus *Lissapiopsis* were found mainly at locality 16. Well-preserved Inoceramae were found at localities 18, 20, 29, and 31.

LOCALITY 1: A few well-preserved fossils were found on the west wall of Arroyo El Pozo about 200 yards northwest of Hacienda El Pozo in the middle of a gray shaly sandstone bed about 33 feet thick. This bed is at the base of the shale series outcropping at Hacienda El Pozo.

LOCALITY 2: Several species were obtained 5 feet above the base of the same bed in which collection 1 was made.

LOCALITY 3: A collection was made at the top of a 10-foot layer of gray, thick-bedded sandstone about 40 feet lower stratigraphically and 100 feet farther northwest than Locality 2.

LOCALITY 4: On the top of Cerro El Pozo are some thin-bedded sandstones containing Ostreas, plant impressions, and a few fragments of petrified wood up to a foot in length.

LOCALITY 5: On the north slope of Cerro El Pozo, immediately below the hard capping layers of the summit of the hill, is exposed about 90 feet of shaly sandstones with lenses of hard gray sandstone about 6 inches thick interspersed at intervals of 5 to 10 feet. Numerous fossils were obtained from the lower part of these beds. This horizon is very distinct because the faunal assemblage contains many species found nowhere else in the section, because the fossils are plentiful, because the fossiliferous strata are about 40 feet thick, and also because the underlying layer is hard, light gray, thick-bedded sandstone about 33 feet thick.

LOCALITY 6: A bed of gray, calcareous sandstone about a foot in thickness forms a distinct horizon on the north slope of Cerro El Pozo because it consists almost entirely of a single species of *Crassatellites*. It occurs about 200 feet lower stratigraphically and 250 yards farther north than Locality 5.

LOCALITY 7: A few poorly preserved fossils were found in gray, thin-bedded sandstone a few yards north of Locality 6 and about 50 feet lower in the section.

LOCALITIES 8-12: Numerous Ostreas occur throughout the section below Locality 7 on the north slope of Cerro El Pozo. At a few horizons other fossils were found. Most of the fossils occur at the base or the top of hard sandstone lenses.

LOCALITY 13: The same fossil horizon as at Locality 6 was found half a mile to the east on the trail to San Ignacio.

LOCALITY 14: An excellent fossil locality about a mile northwest of Boquillas. The main fossiliferous beds are arenaceous shales about 30 feet thick exposed in a shallow syncline at the top of a small hill. This fossil horizon is probably the same as that at Locality 5 on Cerro El Pozo.

LOCALITIES 15 and 16: A number of large gastropods were obtained from shaly sandstones on top of the northern hills of the Carbonera group about 3 miles E.N.E. of Hacienda El Pozo. Locality 16 is at the east end of the top of a ridge overlooking lowlands to the north and separated from the ridge on the east by a narrow canyon. Locality 15 is about 50 yards west of Locality 16.

LOCALITY 17: A few species were obtained from a small exposure of thin-bedded sandstone along the west side of the road which passes around the east side of Cerro Alto (Fig. 3).

LOCALITY 18: A single species of *Inoceramus* was found in abundance on the crest of Cuesta Difunta about 3½ miles N.N.E. of Hacienda El Pozo. The fossils occurred in thin-bedded sandstones at the base of 20 feet of gray, thick-bedded sandstone.

LOCALITY 19: A fairly good fossiliferous horizon was found on a trail on the eroded crest of Cerros Los Indios near the western end of the largest hill. The occurrence is in thin-bedded and shaly sandstones, probably 100 feet thick, overlying green and black shales and surmounted by hard, thick-bedded sandstones on the top of the hill.

LOCALITIES 20 and 21: Fossil collections were made on the south slope of Cuesta Contralvo in a 236-foot unit of shaly to thin-bedded sandstones (Section A-A' unit 37). At Locality 20, large Inoceramae were found in a 5-foot layer of light yellowish gray, coarse-grained, moderately hard sandstone. At Locality 21, Ostreas and Limas occur in a grayish yellow shaly sandstone layer about 8 feet thick lying between layers of hard, yellowish gray sandstones of similar thickness.

LOCALITY 22: *Ostrea saltillensis* Böse and *Lima coahuilensis* Böse occur in great abundance near the base of the north slope of Cuesta del Caballo about 3 miles E.-S.E. of Rancho San Rafael. The fossiliferous beds are light yellow, fine-grained, thin-bedded sandstones which are intercalated in several hundred feet of shaly sandstones.

LOCALITY 23: Numerous well-preserved specimens of *Ostrea sigmoidea* Imlay were obtained from a bed of shaly sandstone on the eroded crest of Cerro Andamia Grande.

LOCALITY 24: *Ostrea saltillensis* Böse and *Lima coahuilensis* Böse were found in a yellowish gray 2-foot sandstone bed about 220 feet stratigraphically below the thick-bedded sandstone layer capping Cerro Andamia Grande.

LOCALITY 25: A number of Ostreas were collected from the shaly sandstone about 100 feet below the top of Cerro Andamia Grande.

LOCALITY 26: Large, flat Inoceramae molds and shells in a layer of hard, gray sandstone are exposed in a road about one mile E.S.E. of Rancho San Rafael.

LOCALITY 27: Another typical occurrence of *Ostrea saltillensis* Böse and *Lima coahuilensis* Böse was found on the south flank of Cerro Andamia Grande at the edge of the plain.

LOCALITY 28: A number of poorly preserved Inoceramae were obtained from thin-bedded sandstones exposed in the small hills about half a mile west of Rancho San Rafael.

LOCALITY 29: Some large gastropods and Inoceramae occur in thick-bedded sandstones at the eastern end of Cerro Mojico.

LOCALITY 30: A number of species were found on the northwest end of Cerro Mojica at the base of gray, nodular shales about 22 feet thick near the bottom of the section.

LOCALITY 31: On Cerro Mojica, large Inoceramae were collected from the floor of a quarry and others were seen in the surrounding walls. The fossil bed is a gray, massive, highly arenaceous limestone about 12 feet thick and is the lowest bed exposed.

Environments.—During the time of deposition of the Difunta formation the environment must have been unfavorable for many forms of life as the fauna consists almost exclusively of pelecypods and gastropods and with few exceptions the number of species in any one horizon is small. One fragment of *Placenticeras,* several shark teeth, some encrusting bryozoa, and a few bones, which are possibly reptilian, are the only other faunal elements. The oyster, *Ostrea sigmoidea* Imlay, occurs throughout the section but is especially abundant in the shaly sandstones

where it occurs throughout hundreds of feet to the exclusion of other forms. This can scarcely be due to complete posthumous destruction of other shells because it is well preserved and also because some of the shells bear encrusting bryozoa which would have been removed if leaching processes had been active. It would seem, therefore, that many of these shaly sandstones were deposited in shallow, probably brackish waters.

However, not all the shaly sandstones are characterized by this dearth of species. Two beds, one at the base of the formation on Cerros Mojica and one at the top (localities 5 and 14), contain an abundant pelecypod and gastropod fauna.

That the gray and brown thick-bedded sandstones were deposited near-shore is suggested by abundant ripple marks, plant remains, and conglomerates. The fauna occurring in thin-bedded sandstones is few in number of individuals and of species and is mostly restricted to large thick-shelled forms belonging to the pelecypod *Inoceramus* and the gastropod *Lissapiopsis*. Some thin-bedded sandstones are filled with the molds of small bivalves, probably *Crassatellites*. These forms evidently lived in much-agitated waters bordering a moderately low land area which was subjected to periodic elevations as shown by the presence of conglomerates. The relief was probably not great because the pebbles in the conglomerates are small. Occasional fragments of bones but no shells are found in the red and green sandstones and shales. The presence of glauconite shows that these beds are marine, and the absence of shells, ripple marks, and plant remains may possibly signify that they were deposited in deeper waters than the gray and brown sandstones. The dark gray shales are likewise almost devoid of fossils. Only a few, very poorly preserved foraminifera were found in them.

State of Preservation.—Most of the fossils of the Difunta formation are preserved as internal molds with portions of the shell adhering. Such forms as the Exogyras, Ostreas, and Pholadomyas retain most of the original shell but the details of the surface ornamentation are generally destroyed. The Inoceramae rarely show any trace of the shell but are otherwise well preserved and are easy to separate from their matrix. The state of preservation is poorer than in many similar beds in the Gulf region but the bulk of the material is susceptible of specific determination.

Biological Analysis.—The fossil collections yielded a mollusk fauna of 64 species of which one is a cephalopod, 30 are gastropods, and 33 are pelecypods. Only five of these species have previously been reported from these beds. In addition to the mollusks, there are a few bryozoa, several shark teeth, and one palm leaf.

The Pelecypoda have all three orders represented. The Prionodesmacea include seven families and eight genera. Within this order the

Inoceramae are the most abundant in species and the Ostreidae have the greatest numbers of individuals. Of the nine species belonging in the genus *Inoceramus*, one is new and the others are related to, or identical with, well-known species from the Montana group of the Western Interior region. Some of the species occur in abundance in very local areas, and only a few occur at several horizons.

The Ostreidae are represented by four species; namely, *Ostrea sigmoidea* Imlay, *Ostrea saltillensis* Böse, *Exogyra costata* var *spinosa* Stephenson (not *Exogira spinosa* Matheron), and *Exogyra ponderosa* Roemer. *Exogyra* occurs in considerable abundance only at localities 5 and 14. *Ostrea* occurs in abundance throughout the entire section in all parts of the area.

The Parallelodontidae are represented by one spscies, *Cucullaea wadei* Imlay. The Trigoniidae are fairly abundant at localities 5 and 14 but the preservation of all specimens is poor. The Pectinidae include a single species which is close to, or identical with, *Pecten cliffwoodensis* Weller. The Limidae are represented by a single species, *Lima coahuilensis* Böse, which occurs in considerable abundance at many horizons and is commonly associated with *Ostrea saltillensis* Böse. The Anomiidae are poorly represented.

The order Anomalodesmacea includes two families and two genera. The Pholadomyidae are represented by three new species, all of which occur only once in the section. The Poromyidae are represented by a single species, *Liopistha (Cymella) bella* Conrad, which occurs at localities 5 and 14.

The order Teleodesmacea includes four families which are represented by six genera. The Crassatellitidae are represented by a single species which occurs in considerable abundance near the top of the section. The Cardiidae are represented by four species of which all specimens are poorly preserved. The Veneridae include three genera and species which are similar to forms from the *Exogyra ponderosa* zone of North Carolina. The Mactridae are represented by a single species.

All the gastropods belong to the order Ctenobranchiata with the possible exception of a single species which is here assigned to the genus *Teinostoma*. Of the thirty species recognized, nine are new and fifteen have been determined only generically.

The order Ctenobranchiata includes eight families and thirteen genera. The Naticidae are represented by two genera and six species. The Turritillidae are represented by the wide-ranging species, *Turritella trilira* Conrad. The families Aporrhaidae and Cancellaridae are doubtfully present. The Strombidae are represented by *Pugnellus* and questionably by *Strombus*. The Buccinidae are represented by *Lissapiopsis* and

Pyropsis. Nine new species are placed under the new genus *Lissapiopsis*. Some of these species are especially large for Cretaceous gastropods. The Volutidae are represented by two genera.

The order Aspidobranchia may be represented by a single poorly preserved species which is questionably assigned to *Teinostoma* and is probably new.

TABLE 2.—*Species definitely identified*

Mollusca	Western Interior	Atlantic and Gulf Coast	
	Pierre	*Exogyra ponderosa* zone	*Exogyra costata* zone
Cucullaea wadei Imlay, n. sp			X
Inoceramus oblongus Meek	X		
Inoceramus pertenuis Meek and Hayden	X		
Ostrea saltillensis Böse		X	
Exogyra costata var. *spinosa* Stephenson		X	X
Exogyra ponderosa Roemer		X	
Lima coahuilensis Böse		X	
Liopistha (*Cymella*) *bella* (Conrad)		X	
Gyrodes spillmani Gabb			X
Turritella trilira Conrad		X	X
Volutilithes? *arispensis* Böse		X	?

The only cephalopod in the fauna is a fragment of a *Placenticeras*. It is closely related to *P. intercalare* (Meek) from the Pierre shale of the Western Interior region.

CORRELATION

In 1906, Böse[8] referred the beds exposed in the hills between the village of Parras and the station of Paila, about 15 miles to the north, to the lower Senonian on the basis of the fossils *Anomia argentaria* Morton, *Lima coahuilensis* Böse, *Inoceramus crippsi* Mantell, *Ostrea glabra* Meek and Hayden, and *Exogyra ponderosa* Roemer. In 1913,[9] he assigned these beds to the Santonian and gave the same evidence as before but supported it by comparing the species with their nearest European relatives.

The writer has found a total of 64 species of mollusks of which 15 are new species, 10 are definitely identified with species in the United States

[8] Emil Böse: *Excursion dans les Environs de Parras* (Mexico), 10th Intern. Geol. Congr., Mexico, Guidebk. 23 (1906) p. 4.

[9] Emil Böse: *Algunas faunas del Cretacico superior de Coahuila y regiones limitrofes*, Soc. Geol. Mexico, Bol., num. 30 (1913) p. 13-15.

(see Table 2 for range), and 11 are compared or closely related to species in the United States (see Table 3).

The faunal lists in tables 2 and 3 show clearly that the Difunta formation belongs in the zone *Exogyra ponderosa* and is equivalent to the Pierre shale of the Western Interior region and the Taylor marl of Texas. Most of the species occur in the upper 1000 feet of the section and correlate that portion definitely with the upper part of the *Exogyra ponderosa* zone. This is shown by the presence of *Exogyra costata* var. *spinoza* Stephenson (not *Exogira spinoza* Matheron), which ranges from the upper part of the *Exogyra ponderosa* zone into the lower part of the *Exogyra costata* zone,[10] as well as by the presence of *Gyrodes spillmani*[11] Gabb which has been reported before only in the lower part of the *Exogyra costata* zone. *Exogyra ponderosa* Roemer is an abundant and widely distributed form whose range is definitely known and whose presence alone is sufficient to place the Difunta formation in the *Exogyra ponderosa* zone. The remainder of the section is Senonian, as shown by the universal presence of *Ostrea sigmoidea* Imlay even in the lowest beds

TABLE 3.—*Mexican species and nearest allied United States species*

Compared or undetermined Mexican species	Nearest allied United States species	Western Interior		Atlantic and Gulf Coast	
		Pierre	Fox Hills	*Exogyra ponderosa* zone	*Exogyra costata* zone
Mollusca:					
Inoceramus sp. a	*Inoceramus sagensis* Owen	X	.....	.....	X
Inoceramus sp. b	*Inoceramus barabini* Morton	X	X	X	.....
Inoceramus cf. *crippsi* Böse (not Mantell)	*Inoceramus crippsi* Böse (not Mantell)	X	X	X	.....
Pecten sp.	*Pecten cliffwoodensis* Weller	.....	.....	X	.....
Anomia cf. *argentaria* Morton	*Anomia argentaria* Morton	.....	.....	X	X
Crassatellites sp.	*Crassatellites neusensis* Stephenson	.....	.....	X	.....
Cyprimeria cf. *gabbi* Stephenson	*Cyprimeria gabbi* Stephenson	.....	.....	X	.....
Lunatia cf. *halli* (Gabb)	*Lunatia halli* (Gabb)	.....	.....	X	X
Lunatia cf. *rectilabrum* Gabb	*Lunatia rectilabrum* Gabb	.....	.....	X	X
Gyrodes cf. *supraplicatus* (Conrad)	*Gyrodes supraplicatus* (Conrad)	.....	.....	X	X
Placenticeras sp.	*Placenticeras intercalare* (Meek)	X	.....	.....	.....

[10] L. W. Stephenson: *Invertebrate fossils of the Upper Cretaceous formations*, N. C. Geol. Econ. Survey, vol. 5, pt. 1 (1923) p. 182.

[11] Bruce Wade: *The fauna of the Ripley formation on Coon Creek, Tennessee*, U. S. Geol. Sur. Prof. Paper 137 (1926) p. 164. See *Gyrodes alveata* Conrad.

on Cerros Mojica. *Ostrea saltillensis* Böse, which is closely related to *Ostrea tecticosta* var. *griftonensis* Stephenson from the *Exogyra cancellata* subzone of North Carolina, occurs abundantly throughout the entire section as low as the basal beds on Cerro Andamia Grande and indicates that these beds also belong in the *Exogyra ponderosa* zone. *Ostrea saltillensis* is common in the San Miguel formation of Texas, which Stephenson [12] confidently correlates with the *Exogyra ponderosa* zone. The presence of *Inoceramus pertenuis* Meek about midway in the section shows a definite correlation with the Pierre which is the approximate equivalent of the *Exogyra ponderosa* zone according to Stephenson.[13] The beds near Hacienda San Rafael are also correlated with the Pierre shale on the basis of an *Inoceramus* which is like *Inoceramus sagensis* Owen. The basal beds on Cerros Mojica contain a fauna which is considerably different from that of the overlying series but whose relationship to the Pierre shale is shown by the presence of two species of *Inoceramus* one of which is like the form commonly called *Inoceramus barabini* Morton and the other like *Inoceramus sagensis* Owen.

The El Pozo-Boquillas area is particularly interesting because there occurs a commingling of the indigenous fauna with many species peculiar to the *Exogyra ponderosa* zone of the Atlantic and Gulf regions and several species peculiar to the Pierre shale and its equivalents in the Western Interior region. The Gulf fauna is strikingly dominant. The large Pholadomyas, the Trigonias, the Ostreas, and various species of pelecypods and gastropods are identical or closely allied to species in the Gulf series. The only species of *Pecten* found is closely related to *Pecten cliffwoodensis* Weller from the *Exogyra ponderosa* zone. The most common form in the series as a whole is *Ostrea sigmoidea* Imlay which is closely related to species of Ostreas from the Gulf series.

Relationship with the Western Interior sea is shown by the Inoceramae. Of the nine species of *Inoceramus,* several are forms which have been found in the Gulf region but are more common in the Western Interior, and certain other species such as *I. pertenuis* Meek and Hayden and *I. oblongus* Meek are known only in the Western Interior. The presence of *I. pertenuis* should be especially noted as its type locality is in the Claggett formation at the mouth of the Judith River in Montana.

A distinctive aspect, entirely unknown in either the Gulf or the Western Interior fauna, is given to the fauna of the Difunta formation by two genera, one a new genus called *Lissapiopsis,* and the other ques-

[12] L. W. Stephenson: *The Taylor age of the San Miguel formation of Texas,* Am. Assoc. Petrol. Geol., Bull., vol. 15 (1931) p. 793-800.

[13] L. W. Stephenson: *Correlation of the Upper Cretaceous or Gulf Series of the Gulf Coastal Plain,* Am. Jour. Sci., 5th ser., vol. 16 (1928) p. 496.

tionably called *Strombus*. The genus *Lissapiopsis* is similar to the living *Melongena* and may be ancestral. Both *Lissapiopsis* and *Strombus* (?) sp. are large for Cretaceous gastropods. These genera may be migrants from faunas of equatorial regions.

TABLE 4.—*Age and correlation of El Pozo-Boquillas section*

<table>
<tr><th colspan="2" rowspan="2">Stages</th><th rowspan="2">Western Interior</th><th colspan="2">Central Texas</th><th colspan="2">Rio Grande Region of Texas</th><th colspan="2">Northeastern Mexico</th><th rowspan="2">El Pozo-Boquillas Area, Mexico</th></tr>
<tr><th>Stephenson</th><th>Böse</th><th>Stephenson</th><th>Böse</th><th colspan="2"></th></tr>
<tr><td rowspan="6">Upper Senonian</td><td>Maestrichtian</td><td>Fox Hills sandstone</td><td>Navarro formation</td><td>?</td><td>Escondido formation
----- ? -----
Olmos formation</td><td>Escondido formation</td><td colspan="2">Escondido formation
---------- ? ----------
Velasco shale</td><td></td></tr>
<tr><td>Campanian</td><td rowspan="3">Pierre shale</td><td>----- ? -----</td><td rowspan="2">Navarro formation</td><td>---- ? ----
San Miguel formation</td><td>Olmos formation</td><td colspan="2">---------- ? ----------</td><td rowspan="2">Difunta formation
----- ? -----</td></tr>
<tr><td rowspan="2">Taylor marl</td><td rowspan="2">Upson clay</td><td>San Miguel formation</td><td colspan="2" rowspan="2">Upper Papagallos or Mendez shale</td></tr>
<tr><td rowspan="2">Lower Senonian</td><td>Santonian</td><td>Taylor marl</td><td>Upson clay</td></tr>
<tr><td>Coniacian</td><td>Niobrara limestone</td><td colspan="2">Austin chalk</td><td colspan="2">Austin chalk</td><td>Lower Papagallos shales</td><td>Upper San Felipe limestone</td><td></td></tr>
<tr><td></td><td>Turonian</td><td>Benton shale</td><td colspan="2">Eagle Ford clay</td><td colspan="2">Eagle Ford clay</td><td colspan="2">Lower San Felipe limestone</td><td></td></tr>
<tr><td></td><td>Cenomanian</td><td>Dakota sandstone</td><td colspan="2">Woodbine sand</td><td colspan="2">Missing</td><td colspan="2">Upper Tamaulipas</td><td></td></tr>
</table>

ALLUVIUM

The Laguna de Mayrán and the plains extending eastward from it and interfingering among the hills are covered by alluvium which varies from fine silt to sand, or even fine gravel. In some places the sand forms dunes a few feet high. A thin coating of gravel, which covers a great deal of the plains both adjacent to and within the hills, has evidently been concentrated on the surface by the removal of the finer particles by strong winds. It is almost invariably composed of pebbles of limestones of

the surrounding mountains and rarely exceeds a quarter of an inch in diameter. These gravels are as abundant in the small plains within the El Pozo-Boquillas hills and north of them (about 15 miles north of the mountains) as on the plains near the mountains. They were probably derived in part from the weathering of the conglomerate beds in the Difunta formation and in part from the Mayrán formation [14] which formerly capped the hills.

IGNEOUS ROCKS

ANDESITIC (?) SILLS AND DIKES

Igneous rocks in the El Pozo-Boquillas hills are confined to dikes and sills whose weathered surfaces can scarcely be distinguished from some of the sandstones in the region. The best outcrops are on Cerros Hormigas. On the north side of the easternmost hill of this group is a nearly vertical dike about two feet wide. It can be followed S. 60° W. for 150 yards, is covered for 100 yards by a sandstone ledge near the top of the hill, and then crops out with a trend of S. 82° W. and dips about 70° NW. It is light gray on a fresh surface but weathers to grayish green and grayish brown. It cuts obliquely across the sandstone and shale beds without affecting their dip and has produced no apparent metamorphism of the adjacent beds.

A similar small dike about 20 inches thick is at the northwestern end of the largest hill of the Hormigas group. At the eastern end of the same hill a sill outcrops over an area about 200 yards long and 30 yards wide. It is of variable thickness, ranging up to 20 feet, and several branches from its central mass are intercalated with layers of sandstone. The thicker portion of the sill contains irregular blocks of sandstone and shale up to 2 feet in diameter. In these the shale is indurated and the sandstone somewhat crystallized, but the sandstone and shale enclosing the sill have undergone almost no alteration. The sill is cut in all directions by veins of calcite up to 2 inches thick.

Another sill in the Cerros Hormigas group is in a small hill about a quarter of a mile east of kilometer post 591. The top of the hill is covered with a greenish brown igneous rock covering an area about 150 feet long from east to west and 60 feet wide from north to south. The overlying sandstones at the base of the hill have been slightly recrystallized at the contact.

A nearly vertical dike about 10 feet thick trends N. 70° E. across the north side of the westernmost hill on the axis of the Difunta Anticline. The characteristics are similar to the rocks already described. A small

[14] R. W. Imlay: *Geology of the western part of the Sierra de Parras*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 1097-1098, 1135.

sill of the same type occurs half a mile to the northeast on the south slope of Cuesta Difunta.

In thin-section the rocks are seen to consist of plagioclase, abundant calcite and magnetite, a little pyrrhotite, limonite, and serpentine. The serpentine and some of the calcite has replaced olivine. The rock is either a basalt or an andesite depending on the plagioclase present, but the latter is highly altered and was not determined.

STRUCTURE

GENERAL FEATURES

The El Pozo-Boquillas area is a part of the Parras synclinal basin. Its structures have been produced by lateral pressures acting in a north-south direction. Folding is the dominant type of structure. The region is crossed from east to west by a series of sinuous folds trending generally E.S.E.-W.N.W., which close to the west as they plunge beneath the alluvial plain of the Laguna de Mayrán. Faulting occurs rarely as overthrusts and cross faults, and abundantly as small bedding faults.

The anticlines are steepest on their north flanks, are usually slightly overturned, and are in places recumbent. Along any one there occurs a number of domes and saddles of which the domes are more overturned. The anticlines and synclines are practically of equal width, varying from 100 yards to over 2 miles across. A cross section of one of these anticlines shows the south flank to be many times longer than the north flank. The dip of the south flank averages about 30 degrees, that of the north flank about vertical or slightly inclined to the south. The axial plane is always inclined to the south. The highest part of the anticline seldom marks the greatest angle of bending. Usually the highest part is gently arched and the greatest bend occurs a short distance north and below the highest part.

The line of greatest bending is marked by a zone of brecciation ranging from a few yards to 50 yards across. In this zone, shales and shaly sandstones are highly twisted, squeezed, and cut by numerous minute bedding faults. The thin- and thick-bedded sandstones are highly fractured and somewhat slickensided but as a rule are sharply folded rather than faulted. In a few places the thick-bedded sandstones have yielded not only by intense folding but by north-south displacement along nearly horizontal thrust planes.

The folds within the basin are all minor compared with the large folds in the surrounding mountains, but they vary considerably in size and may therefore be designated as major and minor folds. Of the four major anticlines the Contralvo Anticline is largest, then in order of size are Andamia Grande, Difunta, and San Ignacio anticlines. The northward-

FIGURE 1. TYPICAL SHALY SANDSTONES
Ridge at the southeast end of the Bajio de Quemado.

FIGURE 2. CURRENT RIPPLE MARKS
Hill half a mile southwest of Cerro Andamia Grande. Crests, 3 inches apart.

FIGURE 3. LARGE OSCILLATION RIPPLE MARKS WITH SUPERIMPOSED CURRENT RIPPLE MARKS
Large ripple marks, about 3 feet apart; small ripple marks, about 2 inches apart. South flank of Cerro Mojica.

SANDSTONES AND RIPPLE MARKS

FIGURE 1. SOUTHERN FLANK OF THE CONTRALVO ANTICLINE
Cuesta Difunta (left), eastern end of Los Indios Anticline (right).

FIGURE 2. RECUMBENT AND OVERTHRUST NORTH FLANK OF THE CONTRALVO ANTICLINE
Cerros Contralvo (left), Cerro Cantaro (right). The steeply dipping sandstones on the crest of Cerro Cantaro have been faulted northward about 250 yards.

facing cuestas carved from the south slopes of these anticlines form the highest hills in the region.

There are twleve minor anticlines which are related to the major anticlines in the following ways: First, they may arise from the Laguna de Mayrán as distinct structures and extend eastward never merging with the major structures as far as traced. Second, they may branch, or finger-out, from the major anticlines and continue eastward or westward approximately parallel to the major anticlines, becoming larger away from their point of origin. These in turn may branch into two or more anticlines. Third, they may be merely short flexures on the south flanks of the major anticlines.

FOLDS

Difunta Anticline.—The Difunta (dead woman) Anticline trends E.S.E. in a sinuous manner. To the west its crest passes through Cerro Difunta. West of this hill the axis trends W.N.W. for nearly 2 miles appearing in a row of low rounded hills in which the center of the anticline is excellently exposed (pl. 3, fig. 3). East of Cerro Difunta the axis trends E.N.E. for about 2 miles, roughtly paralleling Arroyo Difunta which occupies the synclinal valley to the north. The axis then turns E.S.E. for another 2 miles, bends S.E. for a mile, and then continues E.S.E. passing Cerro Alto, which is a prominant hill on the south flank, and then passes out of the region.

The north flank of the Difunta Anticline is short and vertical, or overturned. Its south flank is long, ranging from 1½ to 2 miles in width, and consists of a number of minor crenulations which have an average dip toward the south of 25 to 30 degrees. Structural highs occur at Cerro Difunta and east of Hacienda San Ignacio. A saddle occupies the low plain north of the Hacienda.

Immediately south of the anticlinal high of Cerro Difunta is a small, shallow, east-west syncline. To the south of the syncline is a low, undulating arch about 2 miles broad, whose south flank persists as far as the margin of the belt of hills. From this arch, minor anticlines branch off, both to the east and to the west. Those to the west are named the Mesteñas and the Hormigas-Rinconada anticlines. Those to the east are named the San Isidro, Boquillas, and Carbonera anticlines.

El Pozo-Escondia Anticline.—A narrow, sharp fold appears a mile west of Hacienda El Pozo, trends E.N.E. for 3 miles, and then turns E.S.E. for an equal distance before disappearing beneath the plain. The steep north flank of the fold is excellently exposed on the side of the cut that Arroyo El Pozo has made through the hills north of Hacienda El Pozo. At the arroyo there is an offset of the axis, which may be due to a sudden bending of the fold, or to a small cross-fault along the bed of Arroyo

El Pozo. East of the arroyo the fold becomes much sharper. A quarter of a mile northeast of Hacienda El Pozo on the south flank of Cerro El Pozo, all the beds dip steeply southward, the axis of the fold being shown only by a narrow zone of intense crushing and slickensiding of the beds. This zone can be followed east-southeast from Cerro El Pozo for about 2 miles along the southern margin of the hills. Then the axis bends slightly to the southeast and disappears on the plain. About a mile to the southeast a similar sharply overturned fold trends southeast across the southern side of Cerro Escondia. It is probably a continuation of the El Pozo fold as is indicated by its similar size and shape and also by a change in the strike of the beds in the nearest hills to the north from E.N.E. to E.S.E.

Carbonera, Boquillas, and San Isidro Anticlines.—Three anticlines branch toward the east from the Difunta Anticline. The Carbonera Anticline begins farthest west, about 2 miles E.N.E. of El Pozo, trends eastward for half a mile, and then turns southeast as far as the plain about one mile west of Boquillas. The Boquillas and San Isidro anticlines begin respectively half and one mile north of the Carbonera Anticline on the east side of Cerros Carboneras. They trend southeast 1½ miles parallel to the Carbonera Anticline as far as its easternmost surface expression, then bend east for 1 mile, and finally southeast for 4 miles. In the low hills immediately west of Boquillas is a small fold which is probably the eastward continuation of the Carbonera Anticline, but, if so, the axis of that anticline must also bend eastward paralleling the Boquillas and the San Isidro anticlines.

The Carbonera, Boquillas, and San Isidro anticlines are each about half a mile wide. All three begin as broad ripples on the south flank of the Difunta Anticline. The Carbonera Anticline remains broad and low as far east as Cerro Escondia where it becomes much compressed toward the north but not overturned. The Boquillas Anticline begins to overturn toward the north in the vicinity of Cerro La Cruz and becomes strongly overturned farther east. Near San Isidro the north flank dips about 80° S.W. The San Isidro Anticline is a small, gently arched structure as far east as the Cerros de San Isidro where it enlarges rapidly into an elongate anticlinal high overturned to the north.

Hormigas-Rinconada Anticline.—Most of the hills of the Hormigas group are erosional remnants of the south flank of an anticline. However, the small hill north of the highway near kilometer post 592 and the hill at the southeast corner of the group are synclinal. The only hill south of the road extending from the highway through El Pozo is the crest of a gently arched anticline whose steepest flank is on the north. The axis of this anticline drawn parallel to the syncline to the north is

in line with the axis of an anticline passing along the south side of Cerros Rinconada.

The Rinconada part of the anticline starts as a short, simple fold about three quarters of a mile south of Cerro Difunta and trends W.S.W. for a mile before vanishing beneath the plain. It becomes strongly overturned toward its western exposure and can easily be missed because all the beds are dipping southward. However, its crest is marked by a narrow zone of brecciation and slickensiding. The position of the axis on the plain can be inferred from the syncline to the north. The trough of this syncline becomes broader toward the west, so the crest of the anticline also may become less sharply folded. This shape harmonizes with the shape of the fold at Cerros Hormigas.

Mesteñas Anticlines.—Two small, short, overturned anticlines begin on the western side of the major arch of the Difunta Anticline south of Cerro Difunta and trend W.N.W. Their crests are revealed on the low Cerros Mesteñas by a zone of brecciation containing calcite in great abundance and in places by numerous transparent quartz crystals.

San Ignacio Anticline.—On the eastern side of the Puerto de San Ignacio, about 2 miles northwest of Hacienda San Ignacio, appears a structural ripple in the steeply dipping strata of Cuesta San Ignacio. The ripple traced E.S.E. for 2 miles develops into a small, sharp fold (Pl. 6, fig. 1) which is off-set by a small cross-fault about 1½ miles north of Hacienda San Ignacio. East of the fault the fold trends E.S.E. for a mile then apparently bends to the south for half a mile, and then continues E.S.E. out of the mapped area. The fold broadens toward the east and bears structural highs—(1) a little east of the fault on Cuesta San Ignacio, (2) about 1½ miles north of Cerro Alto, and (3) at Cerro Verdelago.

Contralvo Anticline.—South of the highway between kilometer posts 584 and 585 is exposed a low plunging anticlinal nose which is the western surface expression of the Contralvo Anticline, the longest and largest fold in the region.

The axis of the Contralvo Anticline trends slightly south of east. Starting at the western end of Cerro Contralvo, it trends E.S.E. for about 3 miles, then E. for 5 miles, then E.S.E. for 4 miles. In the westernmost 2 miles of the fold the crest is well preserved, in the eastern portion of Cerro Contralvo the crest is partially destroyed, and in the area to the east it is reduced to low hillocks. The north flank is slightly overturned near the western end of Cerro Contralvo and becomes more overturned to the east. At Cerro Cantaro it is recumbent and faulted. In the lowlands to the east, exposures are poor but remnants of the first

syncline to the north, well preserved on a high narrow ridge about a mile south of Cuesta del Caballo and 4 miles farther east on top of Cerro Yerba Buena, show that the north flank of the Contralvo Anticline is at least vertical and perhaps overturned.

The south flank of the Contralvo Anticline is about 2 miles wide. West of the road which extends from the highway near Cerro Los Postos to Boquillas, the south flank is represented topographically by Cuesta Difunta and the eastern end of Cerro Contralvo. Between these two cuestas lies the minor Los Indios Anticline. East of the road there is only one cuesta, variously called San Ignacio and Los Indios. The average dip of the south flank of the Contralvo Anticline is at least 35 degrees.

Structural highs occur on the Contralvo Anticline at Cerro Cantaro, in the low hill area to the east of Cerro Contralvo, and at Cerro Yerba Buena.

Los Indios Anticline.—A small anticline branches from the Contralvo Anticline about half a mile north of the eastern end of Cuesta Difunta, trends W.S.W. for a mile to Cerro Cigaretta, then turns nearly west passing through Cerros Los Indios. At its eastern end the north flank dips about 60° N., and the south flank about 30° S. Toward the west the anticline gradually becomes larger and more compressed toward the north, and is slightly overturned at Cerros Cigaretta and Los Indios.

Caballo Anticline.—A small, narrow anticline occurs about a mile north of the crest of the Contralvo Anticline. It appears at the west about a mile northeast of Cerro Cantaro and trends east across the Cuesta del Caballo as far as the southeastern end of the Bajio del Quemado. A similar fold appears a mile to the east across the Bajio and continues eastward at least 1½ miles. This fold is slightly overturned near its western end but throughout the remainder of its course the north flank merely dips steeply northward.

Los Postos Anticline.—North of the highway near kilometer posts 580 and 581 rises a conspicuous northwest-southeast trending strike ridge, called Cerro Los Postos, which is in direct line with several smaller and similar strike ridges southeast of the highway that are also called Cerros Los Postos. The strata composing these ridges dip southward at about 40 degrees but near the summit of the highest ridge north of the road the dip becomes as low as 10 degrees. This suggests that the crest of the anticline is only a short distance to the north. Observations made on a small, low hill, half a mile north of kilometer post 580, confirm this idea. The beds at the southern edge of this small hill dip 70° N.W. and a few yards farther north are overturned so as to dip about 85° S.E. The axis of the anticline must therefore be south of this hill and north of Cerros Los Postos.

Mesa Grande Anticline.—A small, gentle fold occurs on the south flank of the Andamia Grande Anticline just south of Mesa Grande. Its north flank is steeper than its south flank but is not overturned. The axis trends nearly due east.

Andamia Grande Anticline.—One quarter of a mile south of Hacienda San Rafael rises a high, broad, hill called Andamia Grande (large platform). This is a structural high at the western end of a major anticline. The western side of the high is broadly rounded and plunges westward at an angle of about 30 degrees. The highest part of the structure occurs about three quarters of a mile to the east. A capping layer of hard sandstone at least 30 feet thick covers the northwest, west, and southwest sides of the high. Erosion has cut deeply into the crest on the east producing a cuesta on the south and a narrow hogback on the north.

A shallow saddle, whose deepest part lies about a mile east of the wagon road across the eastern flank of Cerro Andamia Grande, separates this high from an equally large high in the vicinity of Mesa Grande. In the latter high the crest is deeply dissected, the north flank forms a sharp ridge, and the south flank is represented by Mesa Grande. Mesa Grande owes its apparent flatness to the fact that the beds composing it dip southward at 15 degrees or less, and, also, because the trough of a syncline is preserved along its southern margin.

The axis of the Andamia Grande Anticline trends almost due east. On Cerro Andamia Grande the north flank dips steeply northward but toward the east it gradually becomes overturned. In the hills north of Mesa Grande, about 200 yards north of the axis of the anticline, the north flank of the anticline forms a long steep ridge which ranges from 350 to 300 feet in height. At the top of this ridge the beds dip steeply northward, and at the base the same beds dip about 70° S. The north side of the ridge is cut by a steeply dipping thrust fault. Immediately to the north follows a narrow synclinal valley and then another ridge called Cuesta Presa which parallels the highway for many miles and is on the south flank of the first anticline north of the Andamia Grande Anticline.

The south flank of the Andamia Grande Anticline dips rather gently. On Cerro Andamia Grande the dip is as high as 40° S. but rapidly becomes less steep toward the east. This flank varies in width from one to one and a half miles.

Milagro Anticline.—Four miles northeast of Hacienda San Rafael a long northward-facing cuesta rises from the plain to a height of about 200 feet and extends eastward about 5 miles, gradually broadening and flattening away from its west end. The beds dip from 15° to 45° S. becoming steepest near the plain. The crest of an anticline is exposed

in a small hill about 200 yards west of the main hill. The north flank dips about 45° N.

Mojica Anticline.—Cerros Mojica begin three quarters of a mile east of Ceres (cherry) Station and trend E.S.E. for 2 miles. They are the crests of anticlinal highs from which cuestas are feebly developed. The north slopes are only slightly steeper than the south slopes but, as in the case of the Milagro Anticline, this does not mean that the north flank does not become overturned at depth beneath the alluvial covering.

FAULTS

Faulting is decidedly subordinate to folding in the El Pozo-Boquillas area. Displacement along cross- or thrust-faults is probably not more than 1000 feet at any place. Bedding faults of small extent in shales and shaly sandstone are common in the brecciated zones on the crests of anticlines.

Cerro Cantaro (Pl. 5, fig. 2) is an erosional remnant of the recumbant and faulted north flank of the Contralvo Anticline. The base of the hill is a recumbent syncline with soft red and black shales exposed in the center. The top of the hill consists of thick-bedded sandstones which have been thrust northward about 250 yards over the shales along a nearly horizontal fault plane. These sandstones dip steeply southward at their base, become vertical toward the top of the hill, and even dip northward on the western peak of the hill. The fault passes westward into an overturned anticline. The few exposures in the lowlands to the east do not permit tracing the fault eastward although it probably exists there.

Another thrust fault is well exposed on the north flank of the Andamia Grande Anticline in the hills north of Mesa Grande. The fault plane is nearly vertical and approximately parallel to the bedding. Its lateral extent is not known.

Cross faults were recognized at two places. About 1½ miles north of Hacienda San Ignacio a deep canyon has been eroded along a vertical, north-trending fault. The crest of the San Ignacio Anticline has been off-set about 200 yards, the east wall being displaced northward with respect to the west wall. The fold shown on the east wall is more intensely compressed than the fold on the west wall, which indicates that the greatest movement occurred on the east side of the fault. Another vertical, north-south- trending cross-fault of unknown extent was noted on Cerros Carbonera, on a nearly vertical cliff. The presence of these faults, revealed by peculiar erosional conditions, suggests that there may be many other cross-faults in the area.

FIGURE 1. SAN IGNACIO ANTICLINE
Two miles east of Puerto San Ignacio. Note the sharp syncline to the north (left).

FIGURE 2. SECTION ACROSS THE ANDAMIA GRANDE ANTICLINE
Looking east along the anticline from the crest of Cerro Andamia Grande.

GEOLOGIC HISTORY

Throughout the Campanian, a great thickness of clastic sediments accumulated keeping pace with subsidence in the slowly sinking Parras geosyncline. The basin of the geosyncline contained a broad arm of a sea which extended westward about 100 miles from the Gulf of that time.

This arm of the sea was surrounded by newly elevated land masses on which Lower Cretaceous limestones were undergoing erosion. Periodic re-elevation of these lands produced cycles of sedimentation of which at least a dozen occurred during the deposition of the Difunta formation. Each cycle began with the spreading of limestone gravels over the bottom of the shallow sea. Above the gravels were deposited thick masses of sand probably derived from igneous areas to the west or south of the geosyncline but separated from the sea by areas of Lower Cretaceous limestone. On these sands, laid down in shallow, near-shore waters, were deposited great quantities of calcareous sands and muds in which the silt and clay fractions became increasingly predominant until finally only muds were deposited. Then another re-elevation of the land masses occurred and the cycle of sedimentation was repeated.

Sometime during the late Cretaceous or Tertiary, long after marine sedimentation had ceased in the Parras geosyncline, the region was acted on by great compressive forces in a north-south direction, producing sinuous east-west-trending folds. In the later stage of compression the large anticline along the south side of the Parras geosyncline was thrust northward over its margin. This folding was probably gradual, for faulting is, on the whole, unimportant, but eventually produced steep anticlines whose north flanks are vertical or overturned. Minor intrusions of andesitic magma followed the foldings.

SYSTEMATIC PALEONTOLOGY

Phylum MOLLUSCA

Class PELECYPODA

Genus *CUCULLAEA* Lamarck

Cucullaea wadei Imlay n. sp.

(Plate 14, figure 9)

DESCRIPTION: One specimen from the El Pozo-Boquillas area cannot be distinguished from the *Cucullaea* found by Bruce Wade[15] in the Ripley formation on Coon Creek, Tennessee, and identified by him as *Cucullaea vulgaris* Morton. The writer has compared Wade's figured specimens with specimens of *Cucullaea vulgaris*

[15] Bruce Wade: *The fauna of the Ripley formation on Coon Creek, Tennessee.* U. S. Geol. Sur., Prof. Paper 137 (1926) p. 43-45.

Morton in the National Museum and regards them as two distinct species. *Cucullaea vulgaris*, occurring on the Atlantic coast, is based on an internal mold which exhibits scarcely any characters that can be considered specific but obviously has a different form than the Coon Creek species found by Wade. Wade's species is based on perfectly preserved shells from Tennessee and is now found in Mexico at a slightly lower horizon. The molds of *Cucullaea vulgaris* were considered by Gardner[16] to be the same species as *Cucullaea tippana* Conrad. *Cucullaea tippana* and the Coon Creek form are very similar in general appearance, but the writer believes he finds several minor differences and for the present prefers to give the Coon Creek form a new name.[17]

Shell thick, moderately large, inflated, obliquely produced along the posterior keel. The beak is prominent, orthogyrate, has a distinctly flattened summit, and is situated about two-fifths the length of the shell from the anterior extremity. A prominent rounded umbonal ridge extends from the beak to the lower posterior extremity. Dimensions of the holotype: Length, 67 mm.; height, 60 mm.; convexity of single valve, 28 mm. Dimensions of the Mexican specimen: Length, 75 mm.; height, 59 mm.; convexity, 28 mm.

Cardinal area high rhomboidal with chevron-shaped ligamental grooves varying up to nine in number. The Mexican specimen has four. Hinge line straight and equal to about three-fifths the total length of the shell. Hinge plate narrowest under the beaks. Dentition strong; the medial half of the hinge occupied by short, roughly vertical teeth about 12 to 15 in number; the anterior and posterior portion of the hinge occupied by 3 to 5 transversely striate, hook-shaped teeth which from their inner ends curve mainly outward but slightly ventrally. Muscle scars very distinct, the anterior one high up under the hinge plate, the posterior one bordered along its anterior and ventral margins by a narrow, elevated septum.

Anterior margin abruptly truncated dorsally, passing by a broad curve into the basal margin which is gently convex and oblique; posterior margin subangular below at the extremity, becoming slightly convex above, inclining forward and meeting the hinge line at a variable angle which approximates 125 degrees.

Surface of shell marked by gentle to slightly rugose, irregular concentric undulations, by numerous moderately strong growth lines, and by fine radial lines which are strongest on the medial portion of the shell.

REMARKS: This species is very closely related to *Cucullaea tippana* Conrad. It appears to have a higher and more ventricose shell, the number of medial teeth seems to be greater, the elevated septum anterior to the posterior muscle scar is stronger and more elevated, and the concentric sculpture more prominent.

HOLOTYPE: Cat. No. 32723 U. S. National Museum; Paratypes Cat. No. 15015, University of Michigan, Museum of Paleontology.

OCCURRENCE: Tennessee-Ripley formation, Coon Creek, Sand Hill, McNairy County. Mexico-Difunta formation (found as float on hillside below the horizon of Collection 5), El Pozo- Boquillas area, Coahuila.

Genus *INOCERAMUS Sowerby*

Inoceramus biconstrictus Imlay n. sp.

(Plate 7, figures 1-3; Plate 8, figures 4, 5; Plate 9, figure 1; Plate 10, figure 1)

DESCRIPTION: Twenty-eight specimens of *Inoceramus* were collected from the upper foot of an outcrop of yellow gray, thick-bedded sandstone within an area not

[16] J. A. Gardner: *Upper Cretaceous of Maryland*, Md. Geol. Sur. (1916) p. 529-532.
[17] Holotype figured by Bruce Wade: *op. cit.*, pl. IX, figs. 3 and 4.

greater than 9 square feet. One of these specimens has been identified as *I. oblongus* Meek. The remaining 27 form a morphological series in which the end members are quite distinct and would be called species if found in different horizons or remote localities. However, the presence of intermediate forms between these end members, plus a concomitant size gradation, suggests the possibility that they represent growth stages of one species. The writer regards them as variations of a single species. He sees no value in giving several distinct names to such closely related forms from the same bed. They will therefore be described below as a morphological series in which the individuals vary along several lines. The form figured on Plate 7, figures 1 to 3, is made the type.

The variations in specimens under discussion seem to radiate in three definite directions from a small, regularly eccentric crenulate form very similar to the form which is commonly called *I. barabini*. The individuals belonging to each of these morphological lines have fairly well defined differences in shape which permit them to be assembled in groups characterized by certain salient points in common. The sculpture exhibited by the various individuals is related to their size. The relations between the several groups from the viewpoint of both morphology and size is shown in Table 5.

GROUP A: (Paratypes, U. M. 14961). The specimens in this group are very similar to forms called *I. barabini* but differ in being more inflated, and less cuneate posteriorly. The posterior side is obliquely rounded below, not regularly rounded as in *I. barabini;* the concentric lamellae are more prominent over the greater portion of the shell but become abruptly flattened near the ventral margin; the greatest width is central or slightly anterior. This stage is represented by six specimens. The dimensions of the most complete specimen are as follows: length, 97 mm.; height, 67 mm.; convexity of both valves, 62 mm.

GENERAL DESCRIPTION OF GROUPS B, C, AND D: These forms are larger and usually proportionately longer than those of Group A. The dorsal surfaces bear numerous growth undulations similar in shape and area covered to those on the specimens of Group A. The lowermost undulations flatten out considerably, especially toward the posterior end. Ventral to these undulations the entire shell is suddenly constricted. Above this constriction the shell is quite gibbous, below it the valves rapidly approach closer together. It is succeeded by a slightly crenulated swelling which is in turn constricted but usually less strongly than above. Beyond the second constriction the surface is almost smooth as far as the ventral margins. The latter meet at an obtuse angle except at the posterior extremity where the angle is acute.

SPECIAL CHARACTERISTICS OF GROUP B: Elongate forms; not compressed vertically; not very inflated above the first contriction (Pl. 7, figs. 1-3). The first constriction is strong, the second weak; the swelling between them moderate to faint. Beaks are only slightly incurved. Dimensions of specimen figured: Length, 107 mm., height, 66 m.; convexity of both valves, 60 mm. There are three specimens.

SPECIAL CHARACTERISTICS OF GROUP C: Elongate forms; much compressed vertically (compression may be partly or wholly posthumous); much inflated above the first constriction (Pl. 8, fig. 4). The constrictions are moderately and equally developed; the swelling between them is fairly prominent. Beaks are strongly incurved. Backs are concave. Dimensions of one incomplete specimen are as follows: Height, 78 mm.; convexity of both valves, about 98 mm. There are four specimens.

SPECIAL CHARACTERISTICS OF GROUP D: Subovate forms, no longer proportionately than those of Group A; not compressed vertically; very gibbous above the first

constriction (Paratype, U. M. 14963). The constrictions are strongly and about equally developed. The swelling between them is pronounced but the undulations on its surface are faint. The beaks are only slightly incurved. The undulations on the dorsal surface are quite regular and prominent. Dimensions of only specimen: Length, 85 mm.; height, 75 mm.; convexity of both valves, about 80 mm.

TABLE 5.—*Stage and morphological relationships of several groups of Inoceramus.*

STAGES BASED ON SIZE	GROUPS SHOWING MORPHOLOGICAL RELATIONSHIPS
1st Stage Shell ovate, gibbous, equivalve. Beak forms almost a right angle. Surface ornamented with distinct, regular, more or less prominent, eccentric lamellae. Surface of shell smooth near ventral margin.	*Group A* Forms similar to *I. barabini*
2nd Stage Forms larger and usually proportionately longer than those of 1st stage. Eccentric lamellae on umbonal region are followed ventrally by two constrictions with a gentle convex swelling between, bearing several flattened lamellae. Surface of ventral margins smooth and margins meet at an obtuse angle.	*Group D* — — ? — *Group B* Gibbous form no longer proportionately than those of Group A; not compressed vertically. Deep constrictions. Elongate forms not compressed vertically. Second constriction weak. (Pl. 7, figs. 1–3). *Group C** Elongate forms much compressed vertically. Constrictions moderately and about equally developed. (Pl. 8, fig. 4.)
3rd Stage Shows an increase in size and proportionate length over forms of 2nd stage. Moderately to deeply indented constrictions around the entire ventral-lateral surfaces of the shell. The increase in proportionate length has taken place beyond the first constriction. The ventral margins meet at an acute angle except near the anterior ventral margin. General form of shell similar to *I. oblongus* Meek. Longitudinally oblong in outline; widest posteriorly.	*Group E** Height greater than the convexity; beaks are not strongly incurved. (Pl. 8, fig. 5.) *Group F* Height equal to or slightly less than the convexity; beaks not strongly incurved. (Pl. 9, fig. 1, Pl. 10, fig. 1.). *Group G** Height much less than the convexity; beaks strongly incurved; backs broad and concave.

* Groups C, E, and G may have been compressed posthumously.

GENERAL DESCRIPTION OF GROUPS E, F, AND G: Forms in these groups show an increase in size and proportionate length over those in the preceding groups. Above the first constriction the valves are moderately to strongly inflated, below it they narrow so rapidly to the ventral margin that they meet at an acute angle throughout except at the anterior ventral end. The increase in proportionate length has all taken place beyond the first constriction and is due to greater growth of that part of the shell posteriorly than ventrally.

The sculpture is the same as in the preceding groups. Fragments of shell on one of the specimens show that the surface was marked by ordinary lines of growth.

The general form of the shell is similar to *Inoceramus oblongus* Meek. It is longitudinally oblong in outline; widest near the posterior end. The hinge-line is

TABLE 6.—*Distribution and range of Upper*

El Pozo-Boquillas Region

EXOGYRA PONDEROSA ZONE

MOLLUSCA	Collection 1.	Collection 2.	Collection 3.	Collection 4.	Collection 5.	Collection 6.	Collection 7.	Collection 8.	Collection 9.	Collection 10.	Collection 11.	Collection 12.	Collection 13.	Collection 14.	Collection 15.	Collection 16.	Collection 17.	Collection 18.	Collection 19.	Collection 20.	Collection 21.	Collection 22.	Collection 23.
PELECYPODA:																							
Cucullaea wadei Imlay					X																		
Inoceramus biconstrictus Imlay																				X			
" *oblongus* Meek																				X			
" *pertenuis* Meek and Hayden																		X					
" cf. *crippsi* Böse (not Mantell)						X																	
" sp. a																							
" sp. b																							
" sp. c																							
" sp. d																							
" sp. e														X									
Ostrea sigmoidea Imlay	X	X			X	X		X		X	X	X		X	X		X		X		X	X	X
" *saltillensis* Böse		X							X			X		X					X		X	X	
Exogyra costata var., *spinosa* Stephenson					X									X									
" *ponderosa* Roemer					X									X									
Trigonia sp. a														X									
" sp. b					X																		
" sp. c					X									X									
Pecten sp																	X		X				
Lima coahuilensis Böse	X			X	X														X		X	X	X
Anomia cf. *argentaria* Morton														X									
Pholadomya coahuilensis Imlay																							
" *kellumi* Imlay	X																						
" *mexicana* Imlay	X																						
Liopistha (*Cymella*) *bella* (Conrad)					X									X									
Crassatellites sp					X	X		X		X	X			X									
Cardium sp. a																							
" sp. b														X									
" sp. c														X									
" sp. d		X																					
Cyprimeria cf. *gabbi* Stephenson					X																		
Aphrodina (?) sp														X									
Callista (?) sp			X																				
Cymbophora sp							X																
GASTROPODA:																							
Lunatia cf. *halli* (Gabb)														X									
" cf. *rectilabrum* Gabb																							
" sp																							
Gyrodes spillmani Gabb										X													
" cf. *supraplicatus* (Conrad)					X									X									
" (?) sp																							
Turritella trilira Conrad					X									X									
Anchura (?) sp														X									
Strombus (?) sp																							
Pugnellus (?) sp. a		X			X									X									
" (?) sp. b														X									
" (?) sp. c																							
" (?) sp. d					X									X									
Lissapiopsis inflata Imlay															X								
" *conica* Imlay															X								
" *apiculata* Imlay															X								
" *simplex* Imlay															X								
" *unicarinata* Imlay															X								
" *bicarinata* Imlay															X								
" *tricarinata* Imlay															?								
" *gigantea* Imlay															X								
" *coahuilensis* Imlay															X								
" sp																X							
Pyropsis sp														X									
Sargana sp														X									
Volutilithes (?) *arizpensis* Böse																							
Volutomorpha (?) sp																							
Morea (?) sp														X									
Paramorea (?) sp														X									
Teinostoma (?) sp		X																					
CEPHALOPODA:																							
Placenticeras sp			X																				

X indicates occurrence of same species. A indicates occurrence of allied species. ? indicates

ROSA ZONE

Collection 18.	Collection 19.	Collection 20.	Collection 21.	Collection 22.	Collection 23.	Collection 24.	Collection 25.	Collection 26.	Collection 27.	Collection 28.	Collection 29.	Collection 30.	Collection 31.
X		X											
		X											
		X		X		X	X					X	
		X		X	X				X				

long and straight or slightly upturned posterior to the first constriction. The posterior margin is long and broadly convex. The beaks are equal, medium-sized, almost terminal, raised above the hingle-line, and incurved.

SPECIAL CHARACTERISTICS OF GROUP E: Height greater than the convexity; upper portion of shell only moderately inflated; beaks slightly incurved (Pl. 8, fig. 5). The dimensions of an imperfect specimen are as follows: Length, 154 mm.; height, 88 mm.; convexity of both valves, 73 mm. Two specimens (both may have been compressed laterally posthumously).

SPECIAL CHARACTERISTICS OF GROUP F: Height equal to, or slightly less than, the convexity; upper portion of shell strongly inflated; beaks slightly incurved (Pl. 9, fig. 1, Pl. 10, fig. 1). Dimensions: Length, 160 mm.; height, 81 mm.; convexity of both valves, 82 mm. There are three specimens.

SPECIAL CHARACTERISTICS OF GROUP G: Height much less than the convexity; upper portion of shell strongly inflated; beaks strongly incurved; backs broad and concave (Paratype, U. M. 14959). Dimensions of largest specimen: Length, 195 mm.; height, 80 mm.; convexity of both valves, about 134 mm. The great convexity may be partly accounted for by posthumous compression. There are seven specimens.

HOLOTYPE: No. 14958, University of Michigan. Paratypes: Nos. 14959, 14960, 14961, 14962, 14963, 14968, 14969, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo–Boquillas area, Coahuila, Mexico. Collection 20.

Inoceramus oblongus Meek

1871. *Inoceramus oblongus* MEEK, U. S. Geol. Surv., Terr. for 1870, Ann. Rept., p. 297.

1879. *Inoceramus oblongus* WHITE, U. S. Geol. and Geogr. Surv. Terr., 11th Ann. Rept., p. 285, 286, pl. 2, figs. 1a, b.

DESCRIPTION: Only one specimen of this species was found. Although the anterior end is missing, the remainder of the shell corresponds closely to the type specimen. Compared with the type specimen, the form from the area under discussion is more elongate, the posterior end is thinner, the umbonal region is not as high, and the beaks probably do not rise as far above the hinge-line. But these differences are probably only varietal and the resemblances certainly justify its inclusion in this species.

The dimensions are as follows: Partial length, 141 mm.; height, 80 mm.; convexity of both valves 62 mm.

SPECIMEN: No. 14971 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 20.

Inoceramus pertenuis Meek and Hayden

(Plate 11, figures 1-4)

1856. *Inoceramus ventricosus* MEEK and HAYDEN (May, 1856), Philadelphia Acad. Nat. Sci., Pr., vol. 8, p. 87 (not Sowerby).

1856. *Inoceramus pertenuis* MEEK and HAYDEN (Nov., 1856), Philadelphia Acad. Nat. Sci., Pr., vol. 8, p. 276, 277.

1876. *Inoceramus (Catillus) pertenuis* (Meek and Hayden) MEEK, U. S. Geol. Surv. Terr., Rept., vol. 9, p. 47, 48, pl. 37, figs. 3a, b; pl. 38, figs. 3a b.

DESCRIPTION: Ten specimens have been identified as this species. These are internal molds which retain a little of the fibrous layer of the shell.

Shell medium to small, equivalved, inequilateral, subovate to subquadrangular in outline, very gibbous, cuneate posteriorly; greatest height posterior to the center; greatest convexity through the dorsal portion of the umbones. Lower portion of umbones usually constricted; beaks medium to large, located a little back of the anterior extremity, always swollen, rising high above the hinge-line, then curving forward, inward, and downward so that the apex lies only slightly above the hinge-line. Dimensions of several specimens are as follows:

Specimen	Length mm	Height mm	Convexity mm.
1. (Pl. 11, figs. 1, 2)	87	60	54
2. (Pl. 11, fig. 3)	85	59	55
3. (U. M. 14982)	97	75	53
4. (U. M. 14981)	71	54	58

Hinge-line straight and moderately long; its posterior extremity not preserved in specimens from the area under discussion; it does not reach the anterior end. In lateral view the umbones are seen to arch over the anterior end of the hinge. Below them the anterior margin slopes forward at an angle of about 130 degrees to the hinge-line and then rounds broadly into the ventral margin or meets it at a subobtuse angle; ventral margin gently convex to nearly straight, slightly inclined toward the lower posterior end; posterior margin higher than the anterior, broadly rounded or subtruncated, its extremity slightly above the midheight of the shell.

Surface ornamented with undulations which are almost concentric on the umbones and become eccentric away. They are irregular in size, not strongly elevated, most prominent and closeset on the umbones, gradually becoming farther apart and flatter toward the extremities and base of the shell. Fragments of shell on some of the specimens show fine, thickset growth lines.

Judging from the umbonal regions the young individuals were more ovate in form than the adults, the shell was less gibbous, and the beaks more nearly terminal.

SPECIMENS: Nos. 14983, 14982, 14981, 14980, 14979, 14978, 14984. University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 18.

Inoceramus cf. crippsi Böse (not Mantell)

(Plate 12, figure 1)

DESCRIPTION: One cast of a right valve approaches closely to the forms figured by Roemer[18] and Böse[19] as *Inoceramus crippsi* Mantell. But *I. crippsi* is in reality a Cenomanian species and quite distinct from the American species referred to it. The provisional name will call attention to the relationship of the species from the El Pozo-Boquillas area pending the time when the Inoceramae of North America are monographed.

Shell medium in size, inequilateral, subquadrangular in outline, depressed convex, somewhat cuneate posteriorly; greatest height anterior to the center; greatest convexity through the ventral portion of the umbones. Beaks small, rising a little above the hinge-line, direct, curving slightly inward, located 0.3 the length of the

[18] F. Roemer: *Die Kreidebildungen von Texas und ihre organishen Einschlüsse*, (1852) p. 56, pl. 7, fig. 2. Bonn.

[19] Emil Böse: *Algunas faunas del Cretacico Superior de Coahuila y regiones limitrofes*, Mexico Geol. Inst., Bol. No. 30 (1913) pl. 11, fig. 8.

shell from the anterior extremity. Dimensions of right valve: Length, 90 mm.; height, 70 mm.; convexity, 22 mm.

Most of the hinge posterior to the beak is missing. The anterior dorsal margin slopes from the hinge-line at an angle of 30 degrees, then rounds broadly into the anterior margin; the latter is subtruncated and broad, rounding rather sharply below into the gently convex ventral margin; posterior margin broadly rounded.

Surface marked by concentric ribs of quadrate contour, which are prominent on the dorsal and medial surfaces of the shell but become inconspicuous near the posterior and ventral margins.

SPECIMEN: No. 14975 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 7.

Inoceramus sp. a.

DESCRIPTION: One large internal mold bearing fragments of shell is the basis of this species.

Shell large, transversely subelliptical, moderately compressed; greatest convexity through the anterior dorsal portion of the umbones; greatest height a little anterior to the center. Beaks equal, broad, barely rise above the hinge-line, near the anterior margin. Dimensions: Length (estimated), 185 mm.; height (estimated), 135 mm.; convexity, 62 mm.

None of the margins is entire. Surface ornamented with irregular, eccentric undulations which are fairly prominent on the umbones but gradually become flatter toward the ventral and posterior margins. Fragments of shell show that the surface was covered with fine lines of growth.

REMARKS: This species is similar to *I. sagensis* Owen from the Pierre formation of the Rocky Mountain and Great Plains regions, but the undulations seem to be more eccentric than in that form.

SPECIMEN: No. 15014 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. This specimen was found as float on the north slope of Cuesta Difunta about 100 feet below the horizon of Collection 18.

Inoceramus sp. b.

(Plate 12, figure 5)

DESCRIPTION: Only one fragmentary specimen was found, and the writer does not feel justified in making a specific identification.

Judging from Meek's description and views of Morton's type specimen of *I. barabini*,[20] the Mexican specimen differs in being somewhat longer, the beaks more elevated, and the undulations more prominent.

SPECIMEN: No. 14972 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 31.

Inoceramus sp. c.

(Plate 13, figure 1)

DESCRIPTION: This species is based on one right valve, of which the posterior end is missing.

[20] F. B. Meek: *A report on the invertebrate Cretaceous and Tertiary fossils of the upper Missouri country*, U. S. Geol. Surv., Terr. (Hayden), Rept. 9, vol. 64 (1876) p. 49-50.

Shell large, transversely subovate, laterally compressed; greatest convexity through the umbo on the anterior dorsal portion; greatest height slightly posterior to the center; anterior margin makes a right angle with the hinge-line and then curves obliquely backward and downward into the broadly rounded ventral margin; posterior side long, compressed, and probably rounded; hinge-line, long and straight, beaks small, barely rise above the hinge-line, pointed, slightly incurved, placed directly over the anterior margin.

The surface is ornamented with small, irregular, eccentric undulations which are thickest on the upper part of the umbo, gradually become wider spaced toward its base, and are represented on the ventral and posterior-lateral surfaces by several indistinct swells. Fragments of shell show that the surface was covered with lines of growth spaced at intervals of about one millimeter. Dimensions: Length, probably at least 190 mm.; height, 152 mm.; convexity of right valve, 39 mm.

REMARKS: This species resembles *I. sagensis* Owen from the Pierre formation in size, form, and ornamentation, but the position of the beak is entirely different.

SPECIMEN: No. 14966 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 29.

Inoceramus sp. d.

DESCRIPTION: One distorted, poorly preserved specimen bears a slight resemblance to *I. vanuxemi* Meek and Hayden. The surface is ornamented with distinct, low, angular, concentric lamallae separated by shallow interspaces of about equal width. The dimensions are as follows: Length, about 77 mm.; height, 100 mm.; convexity of both valves, about 50 mm.

REMARKS: This form was associated with numerous other Inoceramae too poorly preserved for specific identification.

SPECIMEN: No. 15028 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 28.

Genus *OSTREA* Linnaeus

Ostrea sigmoidea Imlay n. sp.

(Plate 8, figures 6, 8, 9; Plate 9, figures 2-6; Plate 10, figures 2-4)

DESCRIPTIONS: The following description is based on about 150 specimens collected from the Upper Cretaceous beds of the El Pozo-Boquillas area. The specimen shown on Plate 8 figures 6 and 9 (No. 15033, U. M.) is designated the holotype.

Shell subquadrate to elongate ovate in outline, inequivalve, elongated in the direction of the height. In many specimens the ventral portion of the shell flares either anteriorly or posteriorly or both. The valves are nearly equal in size and usually quite convex, the right valve being in some cases slightly less convex than the left. Either valve may be depressed ventral to the center; medially the ventral portion of the left valve is frequently curved perpendicularly outward from a vertical plane between the valves, the lower anterior and posterior margins being depressed toward the vertical plane; ventral portion of the right valve follows the curve of the left valve closely. Shell wall moderately thick in the umbonal region, becoming thin ventrally. Umbo broadly angular; beak on left valve small, very slightly incurved, pointed, situated centrally, and extending barely beyond the right valve on well-preserved specimens; beak on right valve blunt. Dimensions

of holotype: Height, 50 mm., convexity, 25 mm.; length, 37 mm. Dimensions of specimens collected: Height, averaging 27 mm., never exceeding 65 mm.; convexity variable, averaging 27 mm., for both valves; length exceedingly variable, averaging about 38 mm.

Hinge area broad, semicircular, marked with fine transverse striations and concentric growth lines; the ligamental pit on left valve shallow and elongate triangular, its lower margin strongly convex; the ligamental pit on right valve similar in shape but deeper.

Dorsal margin nearly straight; anterior and posterior margin nearly straight above, diverging slightly away from the extremities of the hinge and becoming sinuous below; ventral margin regularly rounded.

Inner surface of shell smooth; adductor scar large, situated below the midheight and toward the posterior margin; outer surface marked by concentric growth lamellae which are moderately developed; a few left valves bear a slight longitudinal fold a little anterior to the midline of the shell.

REMARKS: Böse [21] found numerous specimens of a species of *Ostrea* in beds of Senonian age at many localities in northern Mexico. He identified this species as *Ostrea glabra* Meek and Hayden but judging from his figured specimens it is the same as *O sigmoidea*.

Ostrea sigmoidea Imlay n. sp. is distinguished from *Ostrea glabra* by its much smaller size, proportionately greater convexity, rather broad dorsal margin, more regular form, by the right valve being nearly as convex as the left in most individuals, and the beak of the right valve being nearly as long as the beak of the left valve.

Ostrea owenana Shumard from the Navarro formation of Texas is very similar to *O. sigmoidea* but is much larger, somewhat less convex, has a thicker shell, and the beak of the left valve projects strongly beyond the beak of the right valve.

Ostrea subspatulata Forbes from the *Exogyra costata* zone of the Gulf region is likewise closely related to *O. sigmoidea* but differs in being much larger and in the beak of the left valve projecting strongly beyond the beak of the right valve.

Ostrea sigmoidea, O. owenana, O. subspatulata, and an undescribed species from the Tombigbee sand member of the Eutaw formation of Alabama [22] form a closely related group characterized by a strong tendency for the ventral portion of the left valve to curve outward and the lower posterior and anterior margins to be depressed, the ventral portion of the right valve showing the opposite but complementary tendency. These species are likewise characterized by moderate to strongly developed growth lamellae.

Ostrea sigmoidea is common throughout the entire formation wherever exposures were studied. It occurs to some extent with other species of pelecypods and gastropods in the shaly sandstones immediately underlying or overlying thick-bedded sandstone layers, but is most abundant in the thick series of calcareous shaly sandstones where in many places it is the only fossil represented in hundreds of feet of strata.

HOLOTYPE: No. 15033; Paratypes: Nos. 15016, 15017, 15021, 15022, 15027, 15029, 15030, 15031, 15032, 15034, 15035, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 1, 2, 5, 6, 8, 10, 11, 12, 14, 15, 17, 19, 23, 24, 25, 30.

[21] Emil Böse: *Op. cit.*, p. 44.

[22] L. W. Stephenson: *Cretaceous deposits of the eastern Gulf Region and species of Exogyra from the eastern Gulf Region and the Carolinas*, U. S. Geol. Sur., Prof. Paper 81 (1914) table 6.

Ostrea saltillensis Böse

(Plate 7, figures 4-9; Plate 8, figures 1-3, 7)

1913. *Ostrea saltillensis* Böse, Inst. Geol. Mexico, Bol. 30, p. 46-47, Lam. VIII, fig. 1-3.

Description: The original description may be translated as follows:

"Shell small, very arched and elongated, form somewhat sickle-like, probably very inequivalved. I have not found with certainty more than the left valve; according to some fragments it appears that the right valve was flat and smooth. The left valve is quite convex, especially in the upper part, while near the lower margin the valve is almost flat. The anterior margin is regularly curved and passes gradually into the lower margin; the posterior margin is concave; the umbo is quite long and curved backward. The ornamentation consists of numerous fine costae which start from the umbo and bifurcate several times; the most regular and frequent bifurcation follows the line of symmetry of the shell in such a way that it appears frequently that the costae start from that line, although in reality they are only branches of some long costae. Further, surface undulations and concentric striations of growth are visible. In the interior the shell is smooth in its greater part; only near the margins fine radial costae are noticeable; the muscle impression is near the posterior margin and is oval to pyramidal. In only two examples is the existence of a ligamental area recognizable; it is elongate triangular.

Dimensions	I mm.	II mm.
Height	29.22	0.5 (probably an error)
Width	15.9	9.2
Thickness	4.2	3.5

"Aquilera found a species in Las Esperanzas which he called *O.* aff *divaricata* Lea and really our species at first glance resembles somewhat *O. divaricata* Lea (*O. sellaeformis* according to Dall) but it is noted immediately that this species is distinguished clearly from that of Las Esperanzas as well as our form by the dilation in the region of the umbo.

"Somewhat nearer to our species is a form from South America described by Burckhardt under the name of *O.* aff *Bomilcaris;* this species was determined by Böhm as *O. ameghinoi,* Iher, and described by Ihering under the name of *Ostrea rocana.* In *O. saltillensis* the costae are much finer than in the South American species, besides our species is more regularly shaped. A true comparison of *O. Saltillensis* with European species is almost impossible because we do not know the right valve."

Among the specimens from the area under discussion are two undoubted right valves. One of these is in normal position inclosed within the margins of the left valve of a rather small specimen. This is probably an immature form as the bifurcating, radial costae are poorly developed and the shell is not very elongate. This right valve is slightly concave but is depressed least in the middle. It bears concentric lines of growth and radial costae, both faintly developed. The beak is blunt.

Another right valve was found separated from the left valve. Although the ventral margin is destroyed, the remainder of the valve shows that it belonged to a larger and probably more mature form than the previously described right valve. This valve is almost flat and near the beak is depressed. The dorsal margin is evenly rounded, the posterior margin slightly concave. The surface is covered with distinct radiating, bifurcating costae which are strongest toward the midline. There are also several faint concentric lines of growth.

In the National Museum are numerous excellently preserved specimens of *O. saltillensis* from the San Miguel formation of Texas. The right valves of the San Miguel forms are curved to conform with the left valves. They are slightly convex dorsally but almost flat or slightly concave ventrally. The outer surface of

the right valve is marked by concentric lines of growth or by faint radiating ribs on the dorsal portion. The hinge area is triangular, somewhat concave, upturned slightly at the ventral margin, and excavated beneath.

The shell of this species is always deflected toward the right.

REMARKS: Stephenson[23] has noted the similarity of *Ostrea tecticosta* var. *griftonensis* Stephenson to *O. saltillensis* Böse but prefers to consider them distinct species for the present.

Ostrea saltillensis occurs in great abundance at the base of the Cuesta del Caballo.

SPECIMENS: Nos. 14990, 14991, 14992, 14993, 14994, 14995, 14996, 15059, 15060, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 2, 9, 12, 14, 19, 21, 22, 24, 25, 27.

Genus *EXOGYRA* Say

Exogyra costata var. *spinosa* Stephenson (not *Exogira spinosa* Matheron)

(Plate 14, figure 7)

1914. *Exogyra costata* STEPHENSON (in part), U. S. Geol. Surv., Prof. Paper 81, pl. 17, fig. 2; pl. 19, figs. 1, 2.

1923. *Exogyra costata* var. *spinosa* STEPHENSON, Invertebrate fossils of the Upper Cretaceous formations, N. C. Geol. Econ. Surv., vol. 5, pt. 1, p. 179-182, pl. 49, figs. 1-6; pl. 50, figs. 1-4.

DESCRIPTION: Specimens from the El Pozo-Boquillas area are medium to small in size. They are poorly preserved but a study of all the forms leaves no doubt as to their identity. The costae are not as regularly arranged as in the typical *E. costata*, the depressions between the costae are frequently wider than the costae, spine-like folds along the crests of the costae are present in some cases but more frequently only the broken bases of the spines are preserved.

SPECIMENS: Nos. 14986, 14987, 14988, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Exogyra ponderosa Roemer

(For synonymy *see* STEPHENSON, N. C. Geol. Econ. Surv., vol. 5, pt. 1 (1923) p. 165-166.)

DESCRIPTION: This species is represented in the collection by 35 specimens, all more or less fragmentary. These specimens represent various stages of growth and show corresponding variations in size.

Böse found *E. ponderosa* in Upper Cretaceous beds to the north of Parras, Coahuila, Mexico. He says (translation):

"In the locality cited (Parras) there is encountered quite a large variety of *Exogyra ponderosa* and the majority of the examples show a species with obtuse apex which starts from the umbo and reaches almost to the lower margin. The shell is smooth and shows only lamellae of growth; radial costae lacking."[24]

[23] L. W. Stephenson: *Invertebrate fossils of the Upper Cretaceous formations*, N. C. Geol. Econ. Surv., vol. 5, pt. 1 (1923) p. 147.

[24] Emil Böse: *Algunas faunas del Cretacico superior de Coahuila y regiones limitrofes*, Mexico Geol. Inst., Bol., No. 30 (1913) p. 50.

The specimens from the beds near El Pozo and Boquillas have the umbonal ridge strongly defined. The groove overlying the ligamental groove is distinct and moderately impressed. The height of the shell seems to be greater in proportion to the length than is average in this species. Some of the smaller shells show small, incipient costae on the umbonal region.

SPECIMENS: Nos. 14976, 14977, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Genus *TRIGONIA* Bruguiere

Trigonia sp. a.

(Plate 12, figure 8)

DESCRIPTION: This species is represented by one internal mold.

Shell small, subtrigonal, equivalved, inequilateral, moderately ventricose anteriorly, becoming compressed posteriorly. Beaks nearly anterior, about one-sixth the length of the shell from the anterior extremity. Dimensions: Length, 32 mm.; height, 20 mm.; thickness, 13 mm.

Dorsal margin broadly concave; anterior margin rounds sharply into the ventral margin; the latter rounds broadly to the posterior margin which is short and probably sharply rounded.

Main surface covered with about twenty ribs which extend from the dorsal surface to the anterior and ventral margins. On the anterior portion the ribs extend forward and downward in a regular curve to the anterior margin. In the medial and posterior portions the ribs become straighter and are directed backward, except near the ventral margin where they curve forward.

SPECIMEN: No. 15004, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Trigonia sp. b.

(Plate 12, figures 2, 6)

DESCRIPTION: Two incomplete specimens belong to a distinct species from that already described.

Shell small, subovate, equivalved, inequilateral, moderately ventricose anteriorly, somewhat compressed posteriorly. Beaks about one-fifth of the length of the shell from the anterior extremity, small incurved, slightly opisthogyrate. Dimensions: Length, 41 mm.; height, 25 mm.; thickness, 14 mm.

Dorsal margin broadly concave, the upturned edges of the two valves forming a keel; anterior margin broadly and regularly rounded, notched; ventral margin broadly rounded, passing in a gentle, regular curve into the posterior margin; the latter not well preserved, but is short, probably squarely truncated, and is situated above the midheight of the shell.

Dorsal surface is slightly concave, about 3 mm. wide at its widest part, crossed transversely by ribs spaced about 1 mm. apart and curving posteriorly. Main surface marked by about 25 tuberculated ribs which originate along the lower margin of the dorsal surface and extend to the anterior and ventral margins. Ribs on anterior portion extend forward and downward in a gentle curve to the anterior margin. From front to rear the ribs become straighter, trending downward in the medial portion and backward in the posterior portion, but always slightly recurved forward near the ventral margin. The surface is covered by fine concentric growth lines.

REMARKS: This form is longer proportionately than *T. eufaulensis* Gabb and has 25 ribs instead of 15 to 18.

SPECIMENS: Nos. 15002, 15003, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 5.

Trigonia sp. c.

(Plate 12, figure 3)

DESCRIPTION: A dozen poorly preserved specimens are the basis of the following description.

Shell medium to small, subovate, equivalved, inequilateral, moderately ventricose anteriorly, becoming much compressed posteriorly. Beaks incurved, slightly opisthogyrous, about one-eighth the length of the shell from the anterior extremity. Dimensions of a large specimen: Length, 40 mm.; height, 28 mm.; thickness, 20 mm. Dimensions of an average specimen: Length, 29 mm.; height, 20 mm.; thickness, 11 mm.

Dorsal margin broadly concave. Anterior and ventral margins together nearly form a semicircle. Posterior margin not well preserved, but is short, probably sharply rounded, and is situated above the midheight of the shell.

The dorsal surface is not preserved sufficiently well to show any ornamentation. The main surface is covered by about 25 moderately prominent, tuberculated ribs which extend from the dorsal surface to the anterior and ventral margins. On the anterior portion the ribs extend downward and forward almost straight for two-thirds of their length and then curve gently and regularly to the anterior margin. On the medial portion of the shell the ribs descend almost straight to the ventral margin but with a slight curve anteriorly in the last third of their length. On the posterior portion the ribs curve backward and downward in a straight line, or are slightly convex toward the anterior end, but always curve slightly anteriorly at the ventral margin. The interspaces between the ribs become narrower toward the posterior end of the shell.

REMARKS: This form is quite similar to *T. cerulia* Whitfield but possesses a few more ribs, the dorsal margin is more concave, and it is apparently thicker. In comparison with *T. marionensis* Stephenson the ribs are more numerous, narrower, and nodose.

SPECIMENS: No. 15000, 15001 University of Michigan, Museum of Paleontology.

OCCURRENCE: *Difunta formation* (Exogyra ponderosa zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Genus *PECTEN* Müller

Pecten sp.

(Plate 14, figure 6)

DESCRIPTIONS: Two fragmentary shells of this genus were obtained from the El Pozo-Boquillas area and are apparently the same species. One is a small portion of the ventral margin and may pertain to either valve. The other is a left valve from which the posterior dorsal margin and the posterior ear have been broken away.

Shell subcircular, the height exceeding the length, left valve depressed convex. Anterior ear separated from the body of the shell by a sulcus. Dimensions of left valve: Length, about 46 mm.; height, about 51 mm.; convexity, 4 mm.

Surface of shell nearly smooth but marked with fine, concentric growth lines; also, very fine radiating lines, scarcely visible macroscopically, are present on the anterior dorsal slope.

REMARKS: These specimens resemble *P. cliffwoodensis* Weller in their sculpture and in the height being the greatest dimension. The fineness of the radiating sculpture will distinguish them from *P. bellisculptus* Conrad from the *Exogyra ponderosa* zone of the Atlantic and Gulf regions, *P. argillensis* Conrad from the *Exogyra costata* zone of New Jersey and Tennessee, and *P. burlingtonensis* Gabb from the *Exogyra ponderosa* and *costata* zones of the Atlantic and Gulf regions. The fine concentric growth lines are totally unlike the strong, concentric, imbricating growth lines of *P. berryi* Stephenson.

SPECIMEN: No. 15005 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 17 and 19.

Genus *LIMA* Bruguiere

Lima coahuilensis Böse

(Plate 14, figures 3-5, 8, 10, 11)

1913. *Lima Coahuilensis* Böse, Inst. Geol. Mexico, Bol. 30, p. 39, Lam. IV, figs. 3-11.

DESCRIPTION: A translation of Böse's description follows:

"Shell small, very convex, somewhat oblique; upper posterior margin almost straight, upper anterior margin straight, passing by a curve into the lower anterior margin; lower posterior margin slightly curved and reuniting with the upper posterior margin in an obtuse angle, lower margin strongly arched. Anterior area scarcely developed; ears small, the anterior larger than the posterior. The ornamentation consists of 30-35 radial ribs, which do not bifurcate, and which are of triangular cross-section in such a way that their highest parts are sharp edged. At the bottom of each interspace between the ribs occur a fine secondary rib. The entire surface is covered with well marked concentric lines of growth, which sometimes produce a light rugose condition on the ribs, especially on the anterior side. The ears do not show ribs but only very pronounced lines of growth.

Dimensions	Right valve	Left valve
Height	19.9 mm.	18.4 mm.
Width	15.0 "	13.7 "
Thickness	5.9 "	5.3 "

"Among American species only *Lima utahensis* somewhat approaches our species exteriorly, but it appears that the ribs of *Lima utahensis* are less numerous (the description does not mention the number) and the authors do not mention secondary ribs in the interspaces; therefore the form probably belongs to a different group.

"Among the species of the Old World there is known only one form from India, *Lima interplicosa*, Stol., which is very close to *Lima coahuilensis*. It has more or less the same number of main ribs and these alternate with secondary ribs of the interspaces; *L. interplicosa* is distinguished from our species by its somewhat longer form and apparently by the stronger granulation of the ribs. *L. interplicosa* occurs in the Ariyalus group of Ninnyur (Upper Senonian).

"Among the European species, *Lima britannica* Woods is probably somewhat near, but is distinguished immediately by the more numerous secondary ribs."

Böse found five complete and several fragmentary specimens on Loma Rinconada, Hacienda de San Lorenzo, Parras, Coahuila, Mexico. Twenty-six more or less fragmentary specimens in the University of Michigan collection from the El Pozo-Boquillas area are identified as this species. These specimens correspond very closely to the description and pictures of the types in all respects but one—namely, that faint secondary ribs rarely occur in the interspaces between the large ribs (Pl. 14, fig. 8). This condition may be due to poor preservation.

REMARKS: *Lima coahuilensis* Böse differs from *Lima oxypleura* (Conrad) from the Black Creek formation of North Carolina in having a greater number of ribs and the ribs on the dorsal slopes more distinctly developed. Compared with *Lima pelagica* var. *covensis* Stephenson from the *Exogyra costata* zone of the eastern Gulf region, the ribs are perhaps sharper. However, the resemblance is very close and the two so-called species may be identical. In the National Museum in a collection of fossils from the Anacaho limestone there was noted a specimen which is certainly *Lima coahuilensis*.

Lima coahuilensis occurs in considerable numbers in many beds throughout the area studied. It occurs in various faunal associations but is commonly associated with *Ostrea saltillensis* Böse. In many places these two forms occur together in great numbers to the exclusion of all others, embedded in characteristic light yellow, fine-grained, thin-bedded sandstones which are intercalated in shaly sandstones. The shells are nearly always preserved and are coal black.

SPECIMENS: Nos. 15018, 15019, 15020, 15021 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 1, 4, 5, 19, 21, 22, 24, 27.

Genus *ANOMIA* (Linnaeus) Müller

Anomia cf. *argentaria* Morton

(Plate 12, figure 4)

DESCRIPTION: Several poorly preserved Anomias were found in the Difunta formation. The best of these, figured here, may be described as follows:

Shell thin, medium size for an *Anomia*, nearly equilateral, subovate, narrowed toward the beak; depressed convex in form. Beak small, inconspicuous, situated centrally and one millimeter back from the margin. Surface marked by fine concentric growth lines.

SPECIMEN: No. 14989 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Genus *PHOLADOMYA* Sowerby

Pholadomya kellumi Imlay, n. sp.

(Plate 16, figures 8, 9)

DESCRIPTION: The description which follows is based on one specimen of which the posterior end is missing but the remainder of the shell is well preserved.

Shell thin, large, equivalve, inequilateral, subelliptical in outline, moderately ventricose. Beaks broad, very prominent, incurved, in contact, situated one-fourth the length of the shell from the anterior extremity. Valves gapping a little anteriorly, probably not posteriorly. Dimensions: Length, about 115 mm.; height, 82 mm.; thickness, 63 mm.

Hinge margin long and straight. Anterior margin broadly rounded; ventral margin gently rounded; posterior margin not preserved.

Surface marked by strong, concentric growth lines and by fifteen radiating costae of which eleven are prominent and acute and four are faint. The antero-dorsal slope is ribless. The first two anterior costae are faint and widely spaced. The eleven prominent costae cover the medial surfaces, vary from moderately strong to strong, are irregularly spaced but are most closely spaced posteriorly. The interspaces are usually deep. The postero-dorsal surface is marked ventrally by two faint costae.

REMARKS: This specie differs from *P. littlei* Gabb from the *Exogyra costata* zone of the Gulf region in its proportionately greater height, in its more prominent beaks, in the anterior margin being broadly instead of sharply rounded above, in the strong costae being more concentrated toward the medial surface of the shell, and in the presence of faint costae both anterior and posterior to the main costae.

P. nodulifera Münster from the Upper Cretaceous of Europe greatly resembles the species from the area under discussion, in form and sculpture but is somewhat smaller and the concentric growth lines are more prominent.[28]

An undescribed species from the Anacacho limestone of Texas differs from *P. kellumi* in being more ventricose, in having thirteen prominent radiating costae which extend farther back on the anterior slope, and in having much broader umbones.

Several species of *Pholadomyas* occurring in the Anacacho limestone are similar to the species found in the Difunta formation of the El Pozo-Boquillas area and if a large number of specimens were available might be found to grade into them. However for the present the Difunta species must be considered to be distinct.

HOLOTYPE: No. 14970, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 1.

Pholadomya mexicana Imlay, n. sp.

(Plate 15, figures 1, 2)

DESCRIPTION: This description is based on two specimens of which the larger one is made the type. The type lacks portions of the ventral and posterior margins. The smaller specimen lacks the postero-dorsal portion of both valves and has been compressed vertically. Much of the original shell material still remains, but is covered with a firmly cemented, fine-grained, yellow sand that can be removed only with great difficulty.

Shell thin, large, equivalve, inequilateral, subelliptical in outline, ventricose. Beaks quite broad, moderately prominent, incurved, in contact, situated one-fourth the length of the shell from the anterior extremity. Valves gapping posteriorly. Dimensions: Length, about 120 mm.; height, about 70 mm.; thickness, 65 mm.

Hinge margin long and straight; hinge not uncovered. Anterior margin rounding broadly into the gently convex ventral margin; posterior margin not well preserved but, judging from the contour of the growth lines, apparently sharply rounded at the extremity which is a little above the midheight.

Surface marked by coarse concentric growth lines and by sixteen radiating costae. The antero-dorsal slope is ribless. The medial slopes bear thirteen narrow ribs which are weak and widely separated anteriorly and moderately strong and closely spaced posteriorly. The postero-dorsal surface bears three faint ribs on its ventral portion.

REMARKS: This species is quite similar to *P. littlei* Gabb from the *Exogyra costata* zone of the Gulf region but does not seem to be as elongate as that form; the anterior margin is broadly rounded above instead of sharply rounded; the ribs on the main body of the shell are not as prominent; the faint ribs on the postero-dorsal surface are not mentioned in the descriptions of *P. littlei*.

An undescribed species from the Anacacho formation is similar to *P. mexicana* but is more robust, has thirteen or fourteen prominent costae which extend farther back on the anterior slope, and the umbo is broader and almost terminal.

[28] C. Moesch: *Monographie der Pholadomyen*, Schweiz. Pälaon. Gesell, Abh., vol. 1 (1874) p. 103-104, pl. 34, fig. 2.

HOLOTYPE: No. 14967; Paratype 15058, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 1.

Pholadomya coahuilensis Imlay, n. sp.

(Plate 15, figure 3)

DESCRIPTION: In the collections from southern Coahuila there is one specimen, consisting of an internal mold with a few fragments of the original shell, which is much like *P. roemeri* Whitfield. The left valve has been slightly compressed, its umbo distorted and partially broken.

Shell fairly large, equivalve, inequilateral, subelliptical in outline, moderately ventricose. Beaks small, incurved, in contact, situated one-fifth the length of the shell from the anterior extremity. Valves gapping a little posteriorly. Dimensions: Length, 93 mm.; height, 49 mm.; thickness, about 48 mm.

Hinge-line long and straight; anterior margin meeting the hinge-line at nearly a right angle and then rounding regularly into the gently convex ventral margin; posterior margin gently rounded below, a little sharper rounded above the midheight of the shell.

Surface marked by twelve pronounced, narrow, acute radiating costae and three faint costae, separated by broad concave interspaces. The anterior dorsal area and a narrow area on the posterior dorsal slopes are ribless. The costae are irregularly spaced and on the left valve are crowded posteriorly. The first anterior costa is faint. The most anterior costae curve slightly anteriorly in passing from the beaks to the ventral margins; the most posterior costae curve posteriorly. The surface is also marked by numerous, irregular concentric lines of growth.

REMARKS: This species differs from *P. roemeri* Whitfield from the Wenonah sand of New Jersey principally in being much larger. The beaks seem to be slightly more prominent, but this may be due to distortion. The posterior end is not sharply rounded above the midheight of the shell. The greatest width is central rather than posterior to the center. The two faint costae on the posterior dorsal slope are lacking in *P. roemeri*.

Pholadomya coahuilensis differs from *P. varicosta* Stephenson from the *Exogyra ponderosa* zone of North Carolina in its larger size, in the smaller number of costae, in the more anterior position of the beaks, and in the more abruptly rounded anterior margin. It differs from *P. littlei* Gabb in its smaller size, in the more anterior position of the beaks, and in the greater number of costae.

HOLOTYPE: No. 14973, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Found as float at the base of the south slope of Cuesta Difunta about 300 yards south of Locality 18. Its position on the slope was far above the reach of the flood waters of Arroyo Difunta. Its condition of preservation shows that it had not been carried far from its place of burial.

Genus *LIOPISTHA* Meek

Liopistha (*Cymella*) *bella* (Conrad)

(Plate 13, figures 3-5)

1875. *Cymella bella* CONRAD, N. C. Geol. Surv., Rept., vol. 1 (by W. C. Kerr) app. A, p. 10, pl. 2, fig. 9.

1876. *Liopistha (Cymella) bella* MEEK, Invert. Cret. and Tert. Foss., Upper Missouri Country, U. S. Geol. and Geog. Survey Terr., vol. 9, p. 228, text figures 25–30.

1907. *Cymella bella* Weller, N. J. Geol. Surv., Paleontology, vol. 4, p. 530, pl. 58, figs. 10-12.

1923. *Liopistha (Cymella) bella* (Conrad) Stephenson, N. C. Geol. Econ. Surv., vol. 5, pt. 1, p. 253-255, pl. 65, figs. 4-8.

Description: Three incomplete casts from the El Pozo-Boquillas area are similar in every way to the forms from the *Exogyra ponderosa* zone of North Carolina.[26] A description of the specimens follows:

Shell subovate in outline, equivalve, inequilateral, moderately convex, becoming less convex posteriorly. Beaks prominent, incurved, touching, situated slightly anterior to the midlength. Dorsal margins sloping from the beaks at an angle of about 125 degrees; the anterior margin slightly steeper than the posterior. Dimensions of the left valve shown on Plate 13, figure 5: Length, about 22.5 mm.; height, 17.5 mm.; convexity, 6 mm. Dimensions of right valve shown on Plate 13, figure 4: Length, 28 mm.; height, 16.5 mm.; convexity, 8 mm.

Anterior margin regularly rounded below, meets the dorsal margin at a subobtuse angle; posterior margin sharply rounded at the extremity which is situated above the midheight; ventral margin gently convex.

Surface marked by eighteen to twenty prominent, broadly rounded, regularly spaced, concentric ribs which terminate at the margin of the lunule and escutcheon-like areas. These are separated by narrow, fairly deep depressions. From the beak, nine to eleven distinct, acute ribs radiate downward to the central and posterior ventral margins. These ribs modify the concentric ribs considerably and scarcely effect the bottoms of the depressions. The radiating ribs near the center of the valve are strongest and gradually become fainter toward the margins.

Remarks: The specimens of *Liopistha (Cymella) bella* from the Difunta formation of the El Pozo-Boquillas area are more closely related to the forms from the Black Creek formation of North Carolina than to the variety from the Navarro formation of Texas mentioned by Stephenson.[27] A similar form occurs in the San Miguel formation of Texas, some of which are like the Difunta form but the majority are more like the Navarro variety. The Navarro variety has broad, round crested costae separated by narrow interspaces about one-third the width of the costae. The number of costae varies from nine to twelve. The interspaces are slightly deeper than in the North Carolina forms. The Difunta forms differ from the North Carolina forms in possessing two or three more costae and the costae are slightly wider.

Specimens: Nos. 15009, 15010, 15011, University of Michigan, Museum of Paleontology.

Occurrence: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Genus *CRASSATELLITES* Krüger

Crassatellites sp.

(Plate 11, figures 5-8)

Description: Numerous specimens of a small species of *Crassatellites* were found at several horizons near the top of the Cretaceous section in the El Pozo-Boquillas area. These forms occur mainly as casts and molds with rarely fragments of shell preserved.

[26] L. W. Stephenson: *Invertebrate fossils of the Upper Cretaceous formations*, N. C. Geol. Econ. Surv., vol. 5, pl. 1 (1923) p. 253-255.

[27] *Op. cit.*, p. 254.

Shell subtrigonal in outline, depressed convex. Beaks small, incurved, prosogyrate, moderately prominent, situated about one-third the length of the shell from the anterior end. The dimensions of several specimens are as follows:

Specimen	Length mm.	Height mm.	Convexity mm.
Left valve	23	18	5
Left valve	24	22	6
Right valve	25	22	6
Right valve	25	21	5.5

The dorsal margins slope from the beaks at an angle of 100 to 115 degrees, the anterior one sloping steeper than the posterior. Anterior margin regularly rounded; ventral margin broadly and regularly rounded; posterior margin sharply rounded to subangular below at the extremity, a short truncation above, rounding into the straight or slightly arched posterior dorsal margin.

The surface is marked by fine growth lines.

REMARKS: This species is quite similar to *Crassatellites neusensis* Stephenson from the *Exogyra ponderosa* zone of North Carolina, but the posterior extremity tends to be less sharply angulated, the posterior truncation somewhat longer, and the angle that the dorsal margins make at the beak is somewhat smaller.

In many places this species forms entire shell beds several inches thick and of considerable areal extent.

SPECIMENS: Nos. 14997, 14998, 14999, 15062 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5, 6, 8, 10, 11, and 14.

Genus *CARDIUM* Linnaeus

Cardium sp. a.

(Plate 13, figure 2)

DESCRIPTION: One left valve from Cerro Mojica is the basis for this species. It consists mainly of an internal mold from which the upper posterior margin has been broken. A portion of the shell is preserved on the lower anterior surface.

Shell thick, subovate in outline, higher than long, moderately convex, somewhat oblique. Beak small prominent, strongly incurved, situated slightly anterior to the midlength of the shell. The umbonal ridge is well marked and forms almost a right angle. The posterior dorsal slope is slightly concave. Dimensions: Length, 21.5 mm.; height, 22 mm.; convexity, 7.5 mm.

Dentition unknown. Dorsal margin of shell broadly arched; antero-dorsal margin rounds broadly into the anterior margin; anterior margin nearly straight, rounding regularly below into the ventral margin, which is inclined slightly toward the lower posterior extremity; posterior margin rather sharply rounded below, then inclined forward above, its upper portion being broken.

Surface marked by about forty radiating ribs which are well preserved on the lower anterior surface of the valve. These ribs are broad, nearly flat-topped, and are separated by narrow, fairly deep depressions. Small, closely spaced transverse ridges are plainly visible in the depressions and are faintly discernible on the ribs.

REMARKS: The marginal outline and the character of the ribs are similar to that of *Cardium carolinense* Conrad from the *Exogyra ponderosa* zone of North Carolina,

but the beak is narrower and more prominent, and the umbonal ridge is strongly angular instead of rounded.

SPECIMEN: No. 15006 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (Exogyra ponderosa zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 30.

Cardium sp. b.

(Plate 13, figures 8, 9)

DESCRIPTION: Two specimens from the El Pozo-Boquillas area have a superficial resemblance to *Cardium longstreeti*, but their poor preservation does not permit definite identification.

Shell medium in size, elongate ovate in outline, a little higher than long, slightly oblique, moderately convex. Beaks moderately prominent, incurved, nearly direct; umbonal ridge well marked, subangular. Shell most inflated centrally. Posterodorsal slope steep; anterior slope broadly rounded but becoming steep near the beak. Dimensions of right valve figured on Plate 13, figure 9 are as follows: Estimated length, 33 mm.; estimated height, 36 mm.; convexity, 11 mm.

Internal margin strongly crenulated. Margins not well preserved. Surface marked by 30 to 35 angular, prominent, radiating ribs which are much wider than the interspaces. There is a suggestion of tubercles on the best preserved ribs.

SPECIMENS: Nos. 15012, 15013, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Cardium (Criocardium) sp. c.

(Plate 13, figure 6)

DESCRIPTION: This species is represented by one specimen which is similar, in the writer's opinion, to *Cardium dumosum* Conrad. It is an internal mold of both valves, lacking the beaks, with a little adhering shell material.

Shell elongate-suboval, slightly oblique, higher than long, moderately convex. The portion of the umbo that is preserved is broadly rounded, not prominent. The posterior slope is fairly steep, the anterior less steep. Dimensions: Length, about 20 mm.; height, 27 mm.; convexity of both valves, 21 mm.

Anterior margin steeply truncated, rounding rather sharply into the slightly convex ventral margin which is slightly inclined toward the lower posterior extremity; posterior margin almost squarely truncated, rounding sharply below and apparently gently above.

Surface much worn but marked by at least fifty low, rounded, radiating ribs, with interspaces of slightly less width. All the interspaces are occupied by rows of spines but usually only the bases are preserved. Only an occasional spine is well preserved, and no system in their arrangement can be observed.

SPECIMEN: No. 15007, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Cardium (Criocardium) sp. d.

(Plate 13, figure 7)

DESCRIPTION: One incomplete internal mold slightly resembles *Cardium tenuistriatum* (Whitfield). Mold subtriangular in outline, moderately convex. Beak situated at about the middle of the hinge-line, prominent, elevated, pointed, and

incurved. Umbonal ridge not prominent, subangular, the posterior slope more abrupt than the anterior. Dimensions: Length, about 27 mm.; thickness, 10 mm.

Surface marked by about forty low, rounded, radiating ribs wider than the interspaces. A few fragments of shell show the presence of spines in the interspaces.

SPECIMEN: No. 15008, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 2.

Genus *CYPRIMERIA* Conrad

Cyprimeria cf. *gabbi* Stephenson

(Plate 10, figure 5)

DESCRIPTION: One poorly preserved specimen bears a close resemblance to *C. gabbi* Stephenson. It is an internal mold of both valves with a few patches of the original shell.

Shell thick, moderately large, subovate in outline, depressed convex, with a decided bend to the left posteriorly. A broad, shallow depression is present just above the posterior truncation. Beak very small, not prominent, and situated about two-fifths the length of the shell from the anterior extremity. Umbonal ridge lacking. Dimensions: Length, 70 mm.; height, 58 mm.; convexity of both valves, about 24 mm. (Valves are slightly gapping ventrally and posteriorly.)

Hinge unknown. Contour of shell is the same as in *C. gabbi* except the postero-dorsal margin is slightly less humped. Fragments of shell on the right valve show that the surface is smooth near the beak and is marked by coarse lines of growth toward the margins.

REMARKS: This specimen differs from the type of *C. gabbi* in being smaller, slightly longer proportionately, and less strongly arched just back of the beak.

SPECIMEN: No. 15025, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 5.

Genus *APHRODINA* Conrad

Aphrodina (?) sp.

(Plate 14, figures 12, 13)

DESCRIPTION: One incomplete internal mold of a right valve probably belongs to this genus. As the structure of the hinge is only faintly indicated, this specimen cannot be definitely excluded from the genus *Veniella*.

The mold is subovate in outline, longer than high, moderately convex. Beak prominent, incurved, prosogyrate, situated about one-third the length of the shell from the anterior extremity. Umbonal ridge broadly rounded. Dimensions: Estimated length, 46 mm.; estimated height, 37 mm.; convexity, 10 mm.

Postero-dorsal margin broadly arched, slightly humped near the beak; posterior margin rather narrow and regularly rounded, the extremity being below the mid-height.

The umbonal ridge bears the impression of numerous concentric growth lines.

REMARKS: This species is similar in general form to *Aphrodina regia* Conrad but is smaller and less strongly humped on the postero-dorsal margin.

SPECIMEN: No. 15024, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

CALLISTA Mörch

Callista (?) sp.

(Plate 12, figure 7)

DESCRIPTION: One fairly well preserved specimen is tentatively referred to this genus.

Shell medium in size, fairly thick, transversely ovate-trigonal in outline. Beak prominent, inflated, prosogyrate, situated one-fourth the total length of the shell from the anterior extremity. Dimensions: Length, 19 mm.; height, 14.5 mm.; convexity, 13 mm.

Dentition unknown. Antero-dorsal margin gently convex near the beak, becoming nearly straight toward the anterior margin; postero-dorsal margin concave and steep; anterior margin rather sharply rounded; ventral margin gently convex; posterior margin broadly rounded below, subangular above.

Surface of shell marked by broad, gently convex, quite regular growth lines which are separated by narrow, deep depressions. These growth lines gradually become wider toward the ventral margin where they approach 1 mm. in width.

SPECIMEN: No. 15026, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 3.

Genus *CYMBOPHORA* Gabb

Cymbophora sp.

(Plate 14, figures 1, 2)

DESCRIPTION: One incomplete internal mold of a right valve with some of the shell adhering on the dorsal margin is questionably referred to this genus.

Shell thin, subelliptical-elongate, inequilateral, broader behind than in front, depressed convex, thickest through the umbones, narrows more rapidly toward the anterior than toward the posterior end. Beak rather broad, moderately prominent, elevated above the hinge-line, incurved, slightly prosogyrate, and situated a little in advance of the middle. Dimensions: Length, 60 mm.; height (incomplete), 35 mm.; convexity, 11 mm.

Internal characters unknown. Antero- and postero-dorsal margins slope gently from the beak, the antero-dorsal margin being steeper. Anterior margin regularly but rather sharply rounded; posterior margin broadly rounded; ventral margin not preserved.

Fragments of shell on the dorsal surface near the beak show that the surface was marked by numerous, fine, concentric lines of growth.

SPECIMEN: No. 14974 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 7.

Class GASTROPODA

Genus *LUNATIA* Gray

Lunatia cf. *halli* (Gabb)

(Plate 20, figures 11-13)

DESCRIPTION: Six poorly preserved internal molds with fragments of shell adhering, probably belong to this species. The specimens are all small, naticoid; whorls five, increasing regularly in size; aperture subovate; surface showing incremental

lines in a few places. Dimensions of medium-size specimen figured: Altitude, 15 mm.; maximum diameter, 11 mm.

REMARKS: The specimens from the El Pozo-Boquillas area have a similar shape to *Lunatia halli* (Gabb) from the *Exogyra ponderosa* and *Exogyra costata* zones of the Gulf and Atlantic coastal regions. They differ from *Lunatia obliquata* (Hall and Meek)[28] from the Pierre and Fox Hills formations of the Western Interior Region in having a less inflated shell and a more elevated spire.

SPECIMEN: No. 15080, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (Exogyra ponderosa zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Lunatia cf. *rectilabrum* Gabb

(Plate 16, figures 3-5)

DESCRIPTION: Two internal molds from Cerro Mojica near Ceres are closely related to this species.

Shell small, subglobose. Spire moderately low. Whorls four or five, increasing rapidly in size. Suture deeply impressed. Body regularly rounded. Aperture apparently subovate. Umbilicus small. Dimensions of figured specimen: Altitude, 10.5 mm.; maximum diameter, 10.3 mm.

REMARKS: In size and shape these specimens look very similar to *Polinices umbilica* Wade from the Ripley formation on Coon Creek, Tennessee. However, the umbilicus is not as large and profound but more like that of *Lunatia rectilabrum*. The specimens are quite similar in shape to *L. rectilabrum* but are both somewhat smaller than is typical of that species.

SPECIMENS: Nos. 15081, 15082, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone): El Pozo-Boquillas area, Coahuila, Mexico. Collection 30.

Lunatia sp.

(Plate 16, figures 6, 7)

DESCRIPTION: This species is represented by one internal mold with portions of the shell adhering.

Shell medium, naticoid. Spire low but well-elevated above body volution. Four or five whorls, increasing regularly in size. Suture slightly impressed. Body whorl bounded by a nodose carina; another row of small nodes present on anterior slope about 1.5 mm. below the carina. Body slightly inflated, regularly rounded. Aperture subovate in outline. Umbilicus narrow and deep, margin angulated. Dimensions: Altitude, 21 mm.; maximum diameter, 21 mm.

SPECIMEN: No. 15079, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (Exogyra ponderosa zone):—El Pozo-Boquillas area, Coahuila, Mexico. Float on Cerro El Pozo.

Genus *GYRODES* Conrad

Gyrodes spillmani Gabb

(Plate 16, figures 1, 2)

1860. *Natica (Gyrodes) alveata* CONRAD, Philadelphia, Acad. Nat. Sci. Jour., 2d ser., vol. 4, p. 289, pl. 46, fig. 45. Preoccupied by *Natica alveata* CONRAD, Rep.

[28] T. W. Stanton: *The fauna of the Cannonball marine member of the Lance formation*, U. S. Geol. Surv., Prof. Paper 128 (1920) p. 35.

Expl. and Sur., P. R. R. Mississippi River to Pacific Ocean; App. Prelim. Geol. Rep. of W. P. Blake, pal. p. 10, 1855.

1861. *Gyrodes spillmani* Gabb, Philadelphia Acad. Nat. Sci., Pr., vol. 13, p. 320.

1892. *Gyrodes petrosus* (Morton) Whitfield, U. S. Geol. Surv., Mon., vol. 18, p. 127, pl. 16, figs. 1-4, (N. J. Geol. Surv., Paleontology, vol. 2, p. 127, pl. 16, figs. 1-4, 1892). The two figured specimens appear to belong to this species.

1907. *Gyrodes petrosus* (Morton) Weller, New Jersey Geol. Surv., Paleontology. vol. 4, p. 689. (In part, not the figured specimens.)

1926. *Gyrodes alveata* Conrad, Wade, U. S. Geol. Surv., Prof. Paper 137, p. 164, pl. 57, figs. 6, 9.

Description: One internal mold with poorly preserved aperture and umbilicus belongs to this species.

Shell depressed, obliquely subelliptical. Five whorls, with body whorl expanding rapidly. Spire slightly prominent; apex acute. Suture distinct and slightly indented, bordered by a narrow flattened area. Shoulder abruptly and steeply depressed. Last two whorls bounded by a carina. Body whorl obliquely depressed in front of shoulder, rounded evenly and gently below medial portion; posterior slope of body whorl slightly contracted immediately below the carina. Umbilicus poorly preserved but apparently moderately large and without an angulated margin. Aperture not preserved. Outer surface marked with distinct incremental lines. Dimensions: Altitude, 23 mm.; greatest diameter, 34 mm.

Remarks: This species is distinguished by its excavated shoulder which is bounded by a sharply angular carina.

Specimen: No. 15078, University of Michigan, Museum of Paleontology.

Occurrence: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 10.

Gyrodes cf. *supraplicatus* (Conrad)

(Plate 17, figures 2, 3; Plate 18, figures 1-3)

Description: Four internal molds from the Difunta formation of the El Pozo-Boquillas region probably belong to this species. Their description follows:

Shell medium to large, depressed elliptical. Only four whorls preserved, the body whorl expanding rapidly to form the greatest bulk of the shell. Spire very low. Suture slightly indented, bordered by a narrow flattened area. Body whorl bordered by a faint, crenulated carina; shoulder obliquely depressed; body whorl more or less strongly flattened in front of shoulder, rounded medially. Umbilicus large, open; umbilical margin bounded by a sharp keel; a second prominent ridge occurs on the inner wall of the umbilicus. Aperture not preserved. Outer surface marked by distinct incremental lines. Dimensions of specimen shown on Plate 17, figures 2, 3: Altitude, 16 mm.; greatest diameter, 30 mm. Dimensions of large specimen on Plate 18, figures 1-3: Altitude, 15 mm.; greatest diameter, 43 mm.

Remarks: The shape of the shell and the doubly carinated umbilicus is very suggestive of *Gyrodes supraplicatus* (Conrad). The long anterior slope is probably due to weathering.

Gyrodes petrosus (Morton) Gabb differs from *G. supraplicatus* in having a higher spire, a single less strongly developed umbilical carina, and lacks crenulations on the body whorl carina near the suture.

Specimens: No. 15083, 15089, University of Michigan, Museum of Paleontology.

Occurrence: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14 and 5.

Gyrodes (?) sp.

(Plate 20, figures 1-3)

DESCRIPTION: One small internal mold will for convenience be placed under this genus, although the specimen is smaller than any figured species that the writer has observed. It will ultimately be placed in a new genus of Naticidae which Stephenson is describing in a monographic study of the Navarro formation.

Shell very small, depressed, elongate elliptical. Whorls three or four in number, rapidly expanding. Spire low. Suture distinct, followed on body whorl by a faint carina. Body whorl obliquely flattened in front, rounded medially, periphery acutely angulated below. Umbilicus broad, margined by a faint carina. Aperture not well preserved but apparently obliquely elliptical. Dimensions: Altitude, 3.4 mm.; greatest diameter, 9.4 mm.

SPECIMEN: No. 15077, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 30.

Genus *TURRITELLA* Lamarck

Turritella trilira Conrad

(Plate 23, figure 7)

(For synonymy *see* STEPHENSON, N. C. Geol. Econ. Surv., vol. 5, pt. 1 (1923) p. 360.)

DESCRIPTION: This species is represented by numerous poorly preserved internal molds. All the specimens are broken, the most complete showing only six whorls. The essential characteristics of the species can be seen.

The spire is high. The whorls are nearly flat on their sides and marked by three revolving ribs. The best-preserved specimens show fine lines between the revolving ribs. On one shell there is a fourth faint revolving rib between the suture and the uppermost rib of the whorl. The suture is distinct and the sutural channel is broad and deep. The aperture is not preserved.

SPECIMENS: Nos. 15103, 15104, 15105, 15106, 15107, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone:—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Genus *ANCHURA* Conrad

Anchura (?) sp.

(Plate 20, figures 4-6)

DESCRIPTION: Eight internal molds with some of the shell adhering probably belong to this genus.

Shell of moderate size for this genus, spire high. Five whorls preserved, probably seven or eight if shell were complete. Apical angle 40 degrees, the sides of the spire maintaining about the same angle or slightly converging; sides of whorls almost flat. Suture moderately impressed. Whorls ornamented with about sixteen strong, quite regularly spaced, round-crested axial ribs, which trend slightly concave toward the front. Aperture elongate, angulated above and below. Outer lip not well preserved, but one specimen shows what is probably the beginning of a lateral expansion (Pl. 20, figs. 4, 5). Inner lip unknown. Dimensions of largest specimen figured. Altitude (incomplete), 23 mm.; greatest diameter, 10.5 mm.

REMARKS: This species somewhat resembles *Anchura johnsoni* Stephenson from

the Black Creek formation of North Carolina. Böse and Cavins[29] have reported *A. johnsoni* from Las Esperanzas, Coahuila. Until better-preserved material is found, even the generic identity of the forms from the El Pozo-Boquillas area must be considered tentative.

SPECIMENS: Nos. 15100, 15101 University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Genus *STROMBUS* Linnaeus

Strombus (?) sp.

(Plate 18, figures 4-6)

DESCRIPTION: One poorly preserved gastropod from Cerros Mojica near Ceres, Coahuila, has a distinctive form and sculpture unlike any species described from the Cretaceous of North America and is therefore worthy of description.

Shell large, subfusiform. Spire moderately low, slopes forming a right angle at apex. Four whorls preserved, increasing regularly in size. Suture distinct. Upper portion of whorls bearing a row of prominent tubercles which progressively become larger and wider spaced toward the aperture. Whorls abruptly constricted below the series of tubercles, the slope below making a right angle with the slope above. Aperture imperfectly preserved, oblong-ovate in shape, terminated at the outer upper margin by a strong projection which may be a tubercle or the expanded outer lip. Inner lip slightly excavated toward the base of the body. Maximum diameter, 85 mm.

REMARKS: This species is characterized by a single row of prominent tubercles, by a low spire, and probably by the rectangular outline of the body.

SPECIMEN: No. 15090, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 29.

Genus *PUGNELLUS* Conrad

Pugnellus (?) sp. a.

(Plate 22, figures 5-7)

DESCRIPTION: Mold medium in size, fusiform, elongate. Spire about one-third the entire length of the body. Whorls five or six, increasing gradually in size; dorsal portion of the body whorl trends upward near the aperture. Suture indented. Aperture elongate and narrow. Lower margin of the outer lip of the mold constricted, the upper margin expanded. Dimensions: Altitude (incomplete), 40 mm.; maximum diameter, 21 mm.

SPECIMENS: Nos. 15095, 15096, 15097, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 2, 5, and 14.

Pugnellus (?) sp. b.

(Plate 23, figures 3, 4)

DESCRIPTION: This species is very much like *Pugnellus* sp. a. from which it is distinguished by its broader aperture, its gently rounded outer lip (on the mold), and

[29] Emil Böse and O. A. Cavins: *The Cretaceous and Tertiary of southern Texas and northern Mexico*, Texas Univ., Bull. 2748 (1927) p. 35-36.

the absence of any tendency to climb of the dorsal portion of the body whorl near the aperture.

SPECIMENS: Nos. 15092, 15093, 15094, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Pugnellus (?) sp. c.

(Plate 22, figures 3, 4)

DESCRIPTION: Shell ovate. Height of aperture about two-thirds the entire length of the shell. Whorls about four, slightly inflated, increasing regularly in size. Suture closely appressed. Aperture moderately wide. Columella not well preserved. The only surface marking on the mold is a wide, shallow spiral sulcus on the upper portion of the body whorl. Dimensions: Altitude, about 21 mm.; maximum diameter, 11.3 mm.

SPECIMEN: No. 15088, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 30.

Pugnellus (?) sp. d.

(Plate 23, figures 9, 10)

DESCRIPTION: Internal mold small, fusiform, Spire low. Five or six whorls; body whorl large; sides of whorls gently convex, smooth. Suture closely appressed. Aperture not preserved. Dimensions of specimen on Plate 23, figures 9, 10: Altitude (incomplete), 25 mm.; greatest diameter, 15 mm.

SPECIMENS: Nos. 15084, 15086, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collections 5 and 14.

Genus *Lissapiopsis* Imlay, n. gen.

DEFINITION: Shell pyriform, inflated, with low spire. Body whorl large, nodes and spines absent or poorly developed, spiral carinae usually present. Aperture elongate ovate, merging gradually into the short, and moderately wide anterior canal. Inner lip smooth and covered with a callus which is thickest at the entrance of the anterior canal. Outer lip simple.

DISCUSSION: A number of large gastropods from the Difunta formation of the El Pozo-Boquillas area show remarkable similarity to the genus *Melongena* and are possibly its Cretaceous precursors. H. Douville[30] has suggested *Eovasum* from the Eocene of Egypt (Mokattam beds) as the ancestors of *Melongena*. However, the columellar plates on *Eovasum* are like those on the living *Vasum* and unlike the smooth columella of *Melongena*. The forms from the Difunta formation are more apt to be the ancestors of *Melongena* than is *Eovasum* because they are anatomically much more like *Melongena* notwithstanding that they are from a much older formation than *Eovasum*.

The Mexican forms have been placed in nine new species under the new generic name *Lissapiopsis*. This genus differs from recent *Melongena* in its shell being more inflated, smoother, and in the upper portion of the aperture being proportionately wider. In all these respects the Miocene species, *Melongena propatulus* Anderson,[31]

[30] H. Douville: *Genre Eovasum*, Jour. Conchyliologie, vol. 66, No. 1 (1921) p. 1-4.

[31] Frank Anderson: *Marine Miocene and related deposits of North Colombia*, Calif. Acad. Sci., Pr., 4th ser., vol. 18, No. 4 (1929) p. 133.

from Colombia bears a stronger resemblance to *Lissapiopsis* than do the Recent species.

GENOTYPE: No. 15067 (holotype of *L. unicarinata* Imlay, n. sp.), University of Michigan, Museum of Paleontology.

Lissapiopsis inflata Imlay, n. sp.

(Plate 19, figures 1-3; Plate 25, figures 2, 5)

DESCRIPTION: Shell large and pyriform. Spire low but standing well up above the body whorl. Whorls five, closely appressed, increasing markedly in size. Suture impressed and obscure. Body abruptly shouldered and inflated, constricted moderately posteriorly and slightly less in front, where it merges into a broad anterior canal which is mostly broken away. Aperture imperfect but apparently broad and elongate ovate. Outer lip broken away. Inner lip moderately excavated at the base of the body, covered with a heavy callus which is thickest at the entrance of the anterior canal. Maximum diameter of holotype (Pl. 19, figs. 1-3): 80 mm. Maximum diameter of small specimen (Pl. 25, figs. 2, 5): 42 mm.

The sculpture is almost entirely destroyed. Faint growth lines and still fainter spiral markings can be detected. The shoulder angle of the last half of the body whorl becomes more prominent anteriorly, and on the largest specimen is separated from the suture by a broad, concave area. There is a wide, faint, concave area below the shoulder angle.

REMARKS: This species is characterized by its inflated body and the broad, subangular shoulder of the body whorl.

HOLOTYPE: No. 15065; paratypes, Nos. 15075, 15074, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 15, one specimen; Collection 16, two specimens; also one specimen found as float on Cerro El Pozo, and two others on the north slope of Cuesta Difunta about a quarter of a mile west of Fossil Locality 18.

Lissapiopsis conica Imlay, n. sp.

(Plate 16, figure 10; Plate 17, figure 1)

DESCRIPTION: Shell large, oval-conic. Spire low but standing well above the body whorl. Whorls four or five, closely appressed. Suture obscure. Body slightly shouldered in front, tapering gradually posteriorly and anteriorly toward the anterior canal of which only the upper portion is preserved. Aperture poorly preserved, but evidently long and narrow. Outer lip broken away. Inner lip covered with a callus, slightly excavated at base of the body. No traces of sculpture. Dimensions: Altitude (incomplete), 94 mm.; maximum diameter, 57 mm.

REMARKS: This species is characterized by its conic outline, elongate and narrow aperture, and slightly shouldered body whorl.

HOLOTYPE: No. 15071, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16. One specimen.

Lissapiopsis apiculata Imlay, n. sp.

(Plate 20, figures 9, 10)

DESCRIPTION: Shell very large, pyriform. Spire depressed but acute and standing well above the body. Whorls four or five, closely appressed, increasing rapidly in size, body almost involving the preceding whorls. Suture obscure. Body obliquely

shouldered and inflated. Shoulder angle obtuse, prominent on the last half of the body whorl, becoming stronger anteriorly and forming a carina which near the aperture is followed above by a broad, shallow, concave area; below carina body whorl is flattened (nearly vertical) for about an inch and then constricted moderately both behind and in front. Aperture elongate ovate. Anterior canal and outer lip broken away. Inner lip reflected, moderately excavated near the base of the body. Maximum diameter of holotype, 90 mm.

REMARKS: This species is characterized by its acute spire, strongly inflated body, and wide, obliquely sloping shoulder terminated by an obtuse angle which becomes a carina toward the front.

HOLOTYPE: No. 15070, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16. Two specimens.

Lissapiopsis simplex Imlay, n. sp.

(Plate 19, figures 4-6; Plate 26, figures 3, 4)

DESCRIPTION: Shell of medium size, oblong-oval. Spire low but standing well above the body. Whorls four or five, closely appressed. No sculpture preserved. Suture obscure. Body whorl inflated and smoothly rounded above, constricted below posteriorly and anteriorly. Aperture broad and elongate ovate, widest above. Anterior canal broken away. Outer lip broken. Inner lip with a thin callus. Maximum diameter of holotype (Pl. 19, figs. 4-6) 40 mm; maximum diameter of large specimen (Pl. 26, figs. 3, 4) 57 mm.

REMARKS: This species is destinguished by its non-carinated, rounded body whorl and general simple form. It may possibly be the young form of some of the larger species described under this genus, *Lissapiopsis*, but until intermediate forms are found the writer chooses to consider it as a distinct species.

HOLOTYPE: No. 15072; paratype, No. 15073, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16. Two specimens.

Lissapiopsis unicarinata Imlay, n. sp.

(Plate 17, figures 4-6)

DESCRIPTION: Shell large, oblong-ovate. Spire blunt and low. Only four whorls preserved, but probably five were present originally; whorls closely appressed, increasing markedly in size. Surface marked with incremental growth lines. Suture obscure. Body whorl inflated, posteriorly well rounded above and constricted below, anteriorly expanded and forming a prominent, obtuse carina slightly above the midheight of the whorl; shoulder broad, steep, and gently convex; body whorl constricted strongly below carina. Aperture broad and ovate, notched posteriorly. Anterior canal mostly broken away. Outer lip expanded, broken below. Inner lip excavated toward the base of the body, covered with a very thick callus, bears a prominent bend slightly above the entrance of the anterior canal. Dimensions: Altitude (lacking anterior canal), 90 mm.; maximum diameter, 76 mm.

REMARKS: This species is characterized by its blunt spire and by the development of a prominent carina on the anterior portion of the body whorl slightly above the midheight.

GENO-HOLOTYPE: No. 15067, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16, One specimen.

Lissapiopsis tricarinata Imlay, n. sp.

(Plate 21, figures 1, 2; Plate 22, figures 1, 2)

DESCRIPTION: Shell large, subovate in outline. Spire low, apex acute. Whorls four or five, closely appressed, increasing markedly in size. Axis of body whorl turned at an angle of about 20 degrees to the axis of the spire. Suture impressed, obscure. Growth lines prominent. Body whorl much inflated, nearly involving the preceding whorls. Surface of body bears three carinae separated by wide, shallow, concave interspaces; upper carina small, occurring about half an inch below the suture; middle carina largest but prominent only near the aperture, occurring slightly above the midheight of the body whorl; anterior carina small, occurring about an inch below the middle carina. Body not noticeably constricted, tapering gradually into the anterior canal which is mostly missing. Aperture large, elongate ovate, widest near its posterior end. Outer lip broken away. Inner lip slightly excavated toward the base of the body whorl, covered with a thick callus. Dimensions: Altitude (lacking anterior canal), 105 mm.; maximum diameter, 90 mm.

REMARKS: This species is characterized by its inflated body, by the presence of three carinae, and by the inclination of the axis of the body whorl to the axis of the spire.

HOLOTYPE: No. 15068, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collected by native guide from the Difunta formation but exact location unknown.

Lissapiopsis gigantea Imlay, n. sp.

(Plate 24, figures 1, 2)

DESCRIPTION: Shell very large, subpyriform. Spire low but standing well above the body whorl. Whorls four or five, closely appressed; body whorl almost involving the preceding whorls. No sculpture preserved. Suture faint. Body whorl inflated above and constricted below, well rounded posteriorly, shouldered anteriorly. Anterior canal mostly broken away but is decidedly bent and probably moderately short and wide. Aperture broad, elongate ovate. Outer lip broken away. Inner lip excavated near the base of the body whorl, covered with a thick callus which is exceptionally thick at the entrance of the anterior canal. Dimensions: Altitude (incomplete), 123 mm.; maximum diameter, 113 mm.

REMARKS: This species is characterized by its large size, inflated body whorl, broad anterior shoulder, bent anterior canal, and general body outline. The anterior shoulder appears broader than it really is, due to the preservation of a greater thickness of shell material there than elsewhere.

HOLOTYPE: No. 15069, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16. One specimen.

Lissapiopsis bicarinata Imlay, n. sp.

(Plate 22, figure 8; Plate 23, figures 8, 11)

DESCRIPTION: Shell very large, pyriform. Spire depressed. Whorls four or five, closely appressed, increasing rapidly in size. Suture impressed, bordered by a faint revolving ridge. Body shouldered and inflated, the upper part bicarinate; the upper carina the stronger, separated from the faint ridge near the suture by a broad, shallow concave area; shoulder broad and steep, becoming very broad near the aperture; body obliquely flattened below carinae, tapering gradually into the

anterior canal which is mostly broken away. Aperture probably elongate ovate. Outer lip broken away. Inner lip bears a thin callus. Dimensions: Altitude (incomplete), 110 mm.; maximum diameter, 100 mm.

HOLOTYPE: No. 15076, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16.

Lissapiopsis coahuilensis Imlay, n. sp.

(Plate 25, figure 1)

DESCRIPTION: Shell large, elongate pyriform. Spire broken away but was probably low. Whorls three or four. Surface marked with strong incremental growth lines which adjacent to the inner lip are crossed by numerous fine, wavy spiral markings. Body whorl perhaps shouldered, elongate, slender, merging into anterior canal which is partially broken away. Anterior canal slightly bent. Aperture elongate, pointed above and below. Outer lip broken. Inner lip excavated toward base of body whorl, covered with a thin callus which is somewhat thickened at the entrance of the anterior canal. Dimensions: Height of specimen, 90 mm.; maximum diameter, 63 mm.

REMARKS: This species is characterized by its elongate columella.

HOLOTYPE: No. 15066, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 16.

Lissapiopsis sp.

(Plate 26, figures 1, 2)

DESCRIPTION: Shell large, elongate, subfusiform. Spire elevated. Whorls five, increasing regularly in size. Suture distinct, closely appressed. Body inflated; whorls of spire well rounded; body whorl gently shouldered in front. Aperture poorly preserved, probably elongate ovate. Dimensions: Altitude (incomplete), 90 mm.; length of spire, 44 mm.; maximum diameter, 59 mm.

SPECIMEN: No. 15091, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 15.

Genus *PYROPSIS* Conrad

Pyropsis sp.

One poorly preserved specimen of *Pyropsis* was found at Fossil Locality 14. It has a nearly flat spire and an abruptly constricted body whorl.

SPECIMEN: No. 15114, University of Michigan, Museum of Paleontology.

Genus *SARGANA* Stephenson

Sargana sp.

DESCRIPTION: One poorly preserved specimen from the Difunta formation belongs to this genus. The shell is sub-pyriform with an almost flat spire. Whorls three or four; suture indistinct. Body whorl large with anterior portion abruptly contracted from the body of the shell. Aperture poorly preserved but apparently subcircular in outline and slightly higher than wide. Anterior canal broken away.

Surface marked by at least six strong spiral ribs separated by much wider interspaces and crossed by numerous less-prominent axial ribs which form nodes at the

intersections. The axial ribs occur at variable intervals but are usually more closely spaced than the spiral ribs.

SPECIMEN: No. 15115, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Genus *VOLUTILITHES* Swainson

Volutilithes ? arizpensis Böse

(Plate 20, figures 7, 8)

1913. *Volutilithes ? arizpensis* BÖSE, Inst. Geol. Mexico, Bol. 30, p. 24-25, pl. I, figs. 6-13.

DESCRIPTION: A number of specimens have been identified as this species. Böse's description may be translated as follows:

"Shell thick, of medium size; form somewhat coarse, composed of five rounded whorls, spire relatively low but perfectly conical; the last whorl is very large. Although the whorls of the mold are perfectly distinct, those of the exterior of the shell are scarcely separated, so that the suture is closely appressed. The last whorl has an oval aperture, rounded in its posterior portion, attenuated in its anterior portion, the narrow anterior canal is preserved only in part. Surface ornamentation consists of slightly prominent longitudinal (axial) ribs on the last whorl, the spire appears smooth, fine spiral striae exist on the anterior portion of the last whorl. Aperture fusiform, lip unknown, columella in the anterior part with a strong oblique fold, secondary folds not observed."

Dimensions of a figured specimen from the El Pozo-Boquillas area: Altitude, 55 mm.; length of aperture, 43 mm.; maximum diameter, 34.5 mm.

SPECIMEN: No. 15085, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Found as float on Cerro El Pozo.

Genus *VOLUTOMORPHA* Gabb

Volutomorpha (?) sp.

(Plate 23, figures 5, 6)

DESCRIPTION: Shell small, fusiform. Spire partially broken away. Body whorl long; three whorls preserved, probably six or seven would normally be present; whorls gently rounded. Suture slightly indented. Body whorl with both axial and spiral sculpture of equal strength; upper part of body whorl marked with five prominent spiral ribs; lower part of body whorl marked with numerous, fine spiral ribs. Aperture imperfect, probably elongate ovate in outline. Dimensions: Estimated altitude, 18 mm.; maximum diameter, 8 mm.

SPECIMEN: No. 15098, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 30.

Genus *MOREA* Conrad

Morea (?) sp.

(Plate 23, figure 12)

DESCRIPTION: One poorly preserved specimen probably belongs to this genus. Only the body whorl is preserved but its size, shape, and sculpture is suggestive of *Morea reticulata* var. *tenuis* Stephenson from the *Exogyra ponderosa* zone (?) of

North Carolina. The shell is small and evidently subovate in outline. The body whorl is large and moderately inflated. The aperture is probably elliptical with a suggestion of an angle above. The surface is marked by ten strong axial ribs. There is no suggestion of a channel between the upper two spiral ribs.

Morea marylandica Gardner from the Monmouth of Maryland and the Ripley of New Jersey is much larger, more elongate, and has a wide concave space between the two posterior spirals. *Morea cancellaria* Conrad from the *Exogyra costata* zone of the Gulf region is much larger and has fewer spiral ribs. *Morea reticulata* Stephenson from the *Exogyra ponderosa* zone (?) of North Carolina has only eight ribs and has a channel between the two posterior spiral ribs.

SPECIMEN: No. 15102, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Genus *PARAMOREA* Wade

Paramorea (?) sp.

(Plate 23, figures 1, 2)

DESCRIPTION: One mold is doubtfully referred to this genus. Shell small, turbinate. Spire moderately prominent, tip broken. Three whorls preserved, probably five if complete; whorls regularly and strongly rounded. Suture poorly preserved, but apparently slightly indented. Surface marked by fine spiral ribs about half the size of the intervening furrows; no trace of axial sculpture. Aperture partially destroyed but probably nearly ovate. Dimensions: Altitude (incomplete), 11.3 mm.; maximum diameter, 7 mm.

REMARKS: This species is somewhat similar to *Spironema tenuilineata* Meek and Hayden from the Fox Hills group, Dakota. However, it lacks a distinctly channeled suture and is less robust.

SPECIMEN: No. 15099, University of Michigan, Museum of Palentology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 14.

Genus *TEINOSTOMA* Adams

Teinostoma (?) sp.

DESCRIPTION: Shell very small, orbicular, external surface highly glazed, posterior surface convex. Spire projecting slightly above the posterior extremity of the body whorl. Whorls of conch two, the body whorl almost concealing the first volution. Protoconch not preserved. Sculpture consisting only of faint incremental lines which are scarcely visible through the glaze of the outer surface. Suture faintly impressed. Body flattened slightly at right angles to the axis of the shell, ovate-elliptical in cross-section with the greatest diameter above the midheight. Aperture broken away, but probably subovate. Umbilical region glazed with callus. Dimensions: Altitude, 2.2 mm.; maximum diameter, 2.9 mm.

REMARKS: This species differs from *Teinostoma prenanum* Wade from the Ripley of Tennessee by its greater size, its relatively greater altitude in relation to its diameter, its slightly projecting spire, its greatest diameter occurring above the midheight of the shell, and by having a strongly rounded rather than an angular periphery.

SPECIMENS: Nos. 15108, 15116, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Collection 3.

Class CEPHALOPODA

Genus *PLACENTICERAS* Meek

Placenticeras sp.

DESCRIPTION: A small fragment of a whorl is identified as this genus and perhaps belongs to the species *P. intercalare* Meek from the Pierre of the Western Interior region of the United States. The fragment shows the umbilical portion and both flanks of a whorl, but the venter is missing. The size is shown by the figures. The sculpture consists of two rows of strong tubercles, one row on the outer half of the flank. The tubercles on the outer row are slightly wider spaced than those of the inner row. Obscure ribs nearly connect the two rows of tubercles. The suture is not visible.

SPECIMEN: No. 15087, University of Michigan, Museum of Paleontology.

OCCURRENCE: Difunta formation (*Exogyra ponderosa* zone):—El Pozo-Boquillas area, Coahuila, Mexico. Found on Cerro El Pozo between the horizons of Collections 4 and 5.

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University of Michigan, Ann Arbor, Mich.
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PLATE 7

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1–3.—*Inoceramus biconstrictus* Imlay, n. sp. Holotype (Univ. Mich. 14958) Coll. 20.

FIGURES 4–9.—*Ostrea saltillensis* Böse

Figure 4 (Univ. Mich. 14992) and Figure 5 (Univ. Mich. 15060). Left valves found as float on Cerro El Pozo.

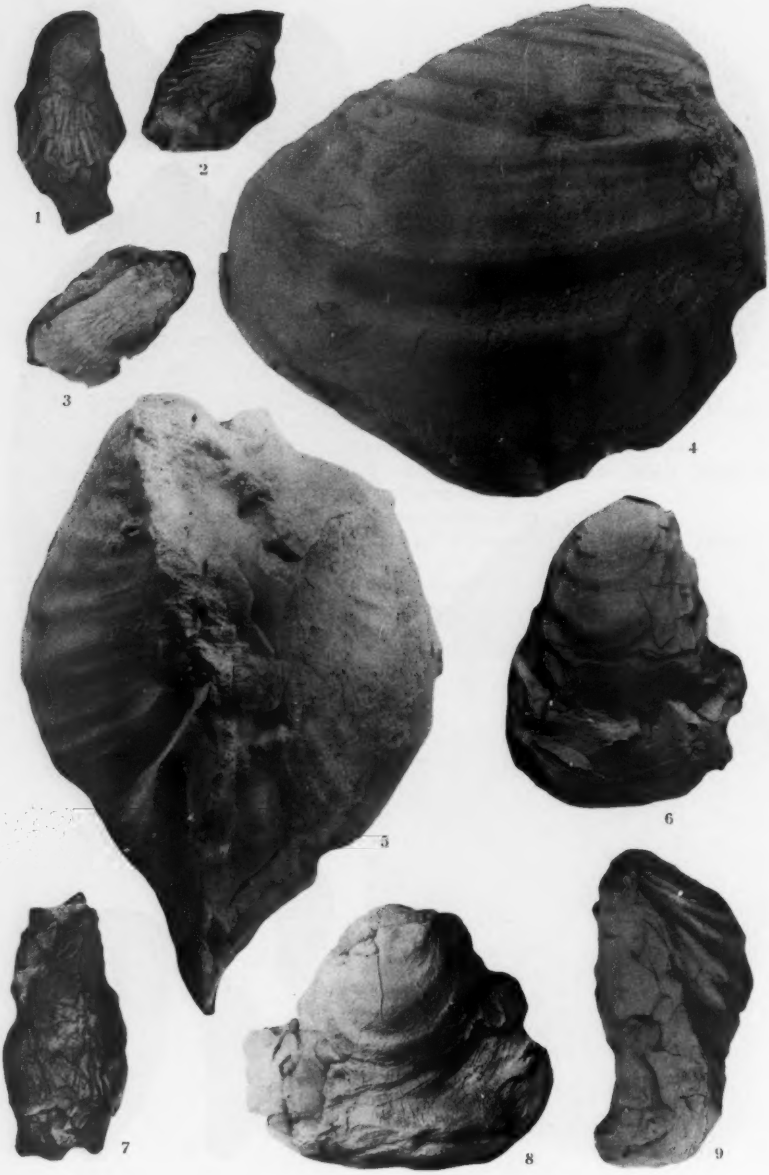
Figure 6. Left valve (Univ. Mich. 14996) Coll. 22.

Figure 7 (Univ. Mich. 14995) and Figure 8 (Univ. Mich. 14994). Left valves. Coll. 21.

Figure 9. Right valve from same specimen as shown in figure 7. X2.

Figures natural size unless otherwise stated.

FOSSILS FROM THE DIFUNTA FORMATION



FOSSILS FROM THE DIFUNTA FORMATION

PLATE 8

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1–3, 7.—*Ostrea saltillensis* Böse
Figure 1 (Univ. Mich. 14993) and Figure 7 (Univ. Mich. 15059). Left valves found as float on Cerro El Pozo.
Figure 2. Left valve (Univ. Mich. 14991) Coll. 25.
Figure 3. Right valve (Univ. Mich. 14990) Coll. 25.
FIGURES 4, 5.—*Inoceramus biconstrictus* Imlay, n. sp.
Figure 4. Paratype (Univ. Mich. 14962) Coll. 20.
Figure 5. Anterior end of paratype (Univ. Mich. 14960) Coll. 20.
FIGURES 6, 8, 9.—*Ostrea sigmoidea* Imlay, n. sp.
Figures 6 and 9. Left valve and side view of holotype (Univ. Mich. 15033) Coll. 23.
Figure 8. Left valve (?) (Univ. Mich. 15032) Coll. 23.
Figures natural size.

PLATE 9

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Inoceramus biconstrictus* Imlay, n. sp.
Paratype (Univ. Mich. 14968) Coll. 20.

FIGURES 2–6.—*Ostrea sigmoidea* Imlay, n. sp.
Figures 2 and 6. Interior and exterior of a right valve (Univ. Mich. 15022) Coll. 25.
Figure 3. Edge view (Univ. Mich. 15030) Coll. 23.
Figure 4. Left valve (Univ. Mich. 15035) Coll. 23.
Figure 5. Interior of left valve (Univ. Mich. 15031) Coll. 23.

Figures natural size.

FOSSILS FROM THE DIFUNTA FORMATION

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 10

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Inoceramus biconstrictus* Imlay, n. sp.
Paratype (Univ. Mich. 14968) Coll. 20. Dorsal view of specimen shown on Plate 9, figure 1.

FIGURES 2–4.—*Ostrea sigmoidea* Imlay, n. sp.
Figure 2. Edge view (Univ. Mich. 15027) Coll. 23.
Figure 3. Dorsal view (Univ. Mich. 15029) Coll. 23.
Figure 4. Left valve (Univ. Mich. 15016) Coll. 19.

FIGURE 5.—*Cyprimeria* cf. *gabbi* Stephenson
Internal mold of left valve with fragment of shell adhering. (Univ. Mich. 15025) Coll. 5.

Figures natural size.

PLATE 11

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1–4.—*Inoceramus pertenuis* Meek and Hayden

Figures 1 and 2. Right valve and anterior view of same specimen (Univ. Mich. 14979) Coll. 18.

Figure 3. Dorsal view (Univ. Mich. 14980) Coll. 18.

Figure 4. Right valve (Univ. Mich. 14983) Coll. 8.

FIGURES 5–8.—*Crassatellites* sp.

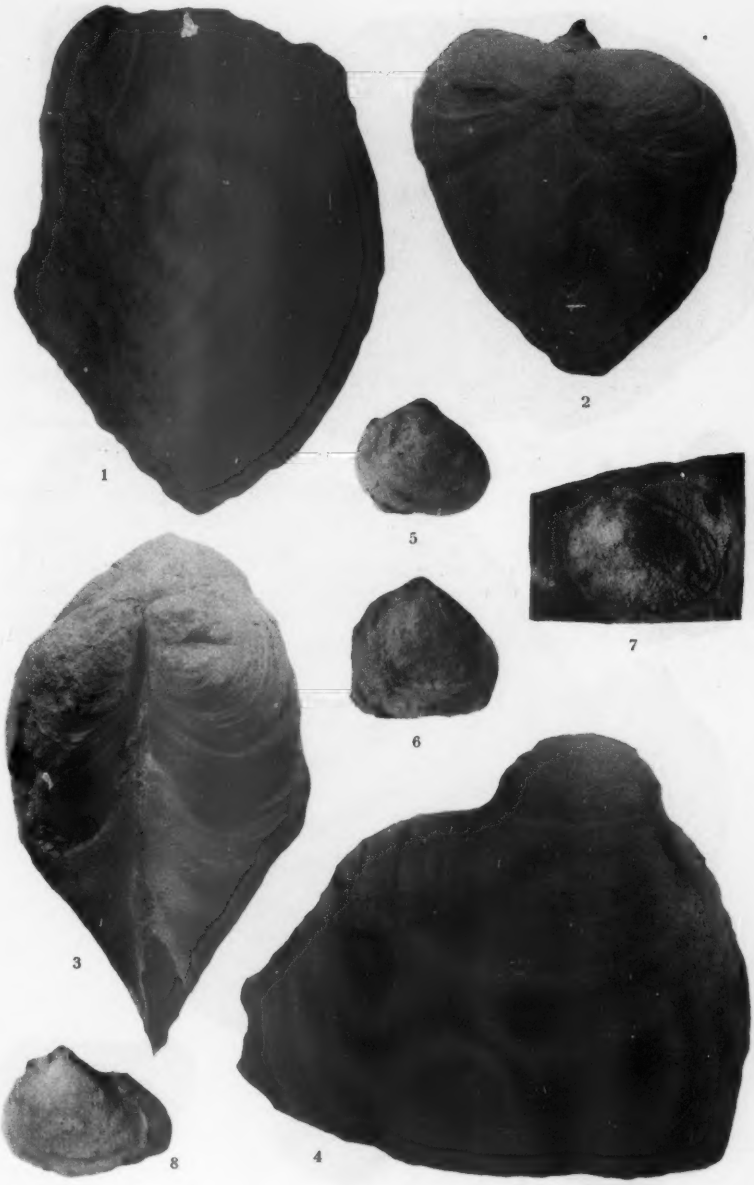
Figure 5. Internal mold of left valve (Univ. Mich. 14997) Coll. 10.

Figure 6. Internal mold of left valve (Univ. Mich. 14998) Coll. 8.

Figure 7. Internal mold of left valve (Univ. Mich. 14999) Coll. 7.

Figure 8. Weathered interior of right valve (Univ. Mich. 15062) Coll. 8.

Figures natural size.



FOSSILS FROM THE DIFUNTA FORMATION

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 12

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Inoceramus* cf. *crippsii* Böse (not Mantell)
Right valve (Univ. Mich. 14975) Coll. 7.
FIGURES 2, 6.—*Trigonia* sp. b
Figure 2. Left valve (Univ. Mich. 15003) Coll. 5.
Figure 6. Right valve (Univ. Mich. 15002) Coll. 5.
FIGURE 3.—*Trigonia* sp. c
Left valve (Univ. Mich. 15000) Coll. 14.
FIGURE 4.—*Anomia* cf. *argentaria* Morton
(Univ. Mich. 14989) Coll. 14.
FIGURE 5.—*Inoceramus* sp. b
(Univ. Mich. 14972) Coll. 30.
FIGURE 7.—*Callista* (?) sp.
(Univ. Mich. 15026) Coll. 3.
FIGURE 8.—*Trigonia* sp. a
Left valve (Univ. Mich. 15004) Coll. 14.
Figures natural size.

PLATE 13

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Inoceramus* sp. c
(Univ. Mich. 14966) Coll. 29.

FIGURE 2.—*Cardium* sp. a
Left valve (Univ. Mich. 15006) Coll. 30.

FIGURES 3–5.—*Liopistha* (*Cymella*) *bella* (Conrad)
Figure 3. Left valve (Univ. Mich. 15010) Coll. 14.
Figure 4. Right valve (Univ. Mich. 15011) Coll. 14.
Figure 5. Left valve (Univ. Mich. 15009) Coll. 5.

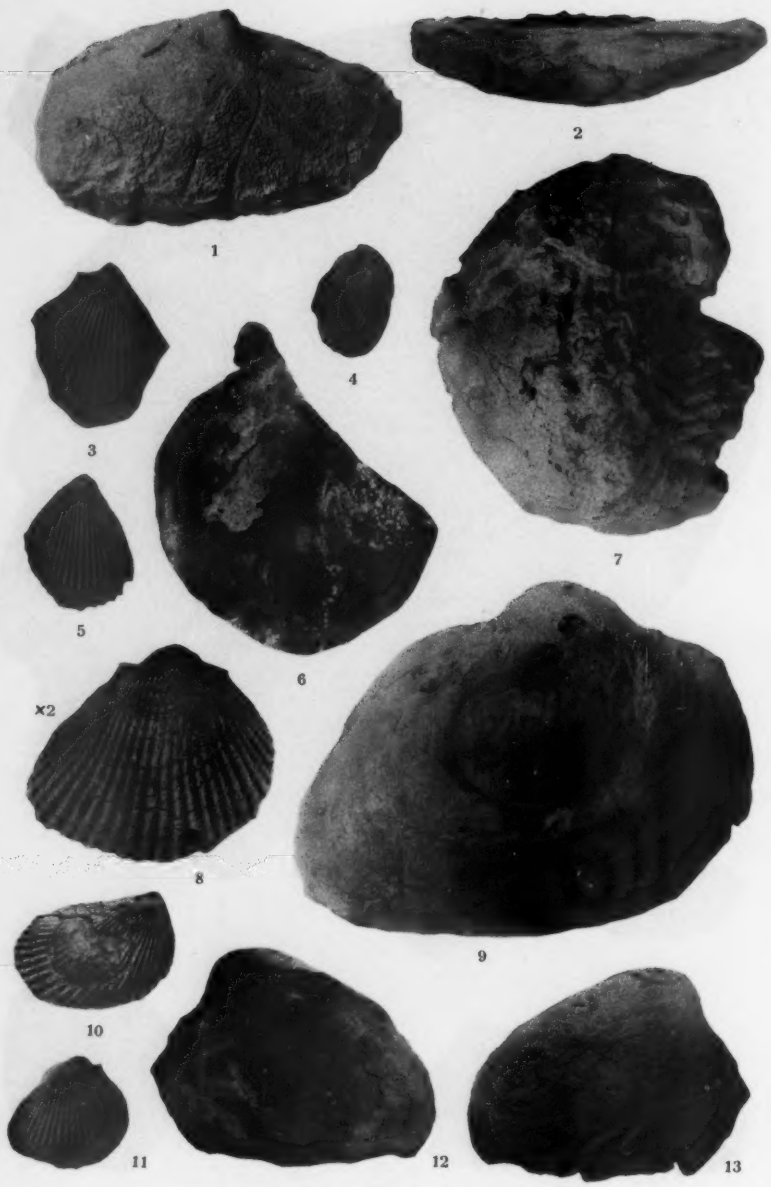
FIGURE 6.—*Cardium* (*criocardium*) sp. c
Right valve (Univ. Mich. 15007) Coll. 14.

FIGURE 7.—*Cardium* (*criocardium*) sp. d
Right valve (Univ. Mich. 15008) Coll. 2.

FIGURES 8, 9.—*Cardium* sp. b
Figure 8. Right valve (Univ. Mich. 15012) Coll. 14.
Figure 9. Right valve (Univ. Mich. 15013) Coll. 14.

Figures natural size.

FOSSILS FROM THE DIFUNTA FORMATION



FOSSILS FROM THE DIFUNTA FORMATION

PLATE 14

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Cymbophora* sp.
Right valve (Univ. Mich. 14974) Coll. 8.

FIGURES 3–5, 8, 10, 11.—*Lima coahuilensis* Böse
Figure 3. Left valve (Univ. Mich. 15018) Coll. 5.
Figures 4, 8, 11. Right valve and edge view (Univ. Mich. 15019) Coll. 5.
Figure 5. Left valve (Univ. Mich. 15020) Coll. 5.
Figure 10. Right valve (Univ. Mich. 15061) Coll. 5.

FIGURE 6.—*Pecten* sp.
(Univ. Mich. 15005) Coll. 23.

FIGURE 7.—*Exogyra costata* var. *spinosa* Stephenson
(Univ. Mich. 14988) Coll. 5.

FIGURE 9.—*Cucullaea wadei* Imlay, n. sp.
Right valve found as float on north slope of Cerro El Pozo. (Univ. Mich. 15015).

FIGURES 12, 13.—*Aphrodina* (?) sp.
Interior and exterior view of a mold (Univ. Mich. 15024) Coll. 14.

Figures natural size.

PLATE 15

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Pholadomya mexicana* Imlay, n. sp.
Holotype (Univ. Mich. 14967) Coll. 1.
FIGURE 3.—*Pholadomya coahuilensis* Imlay, n. sp.
Holotype (Univ. Mich. 14973). Float on south slope of Cuesta Difunta, about 300 yards south of locality 18.
Figures natural size.

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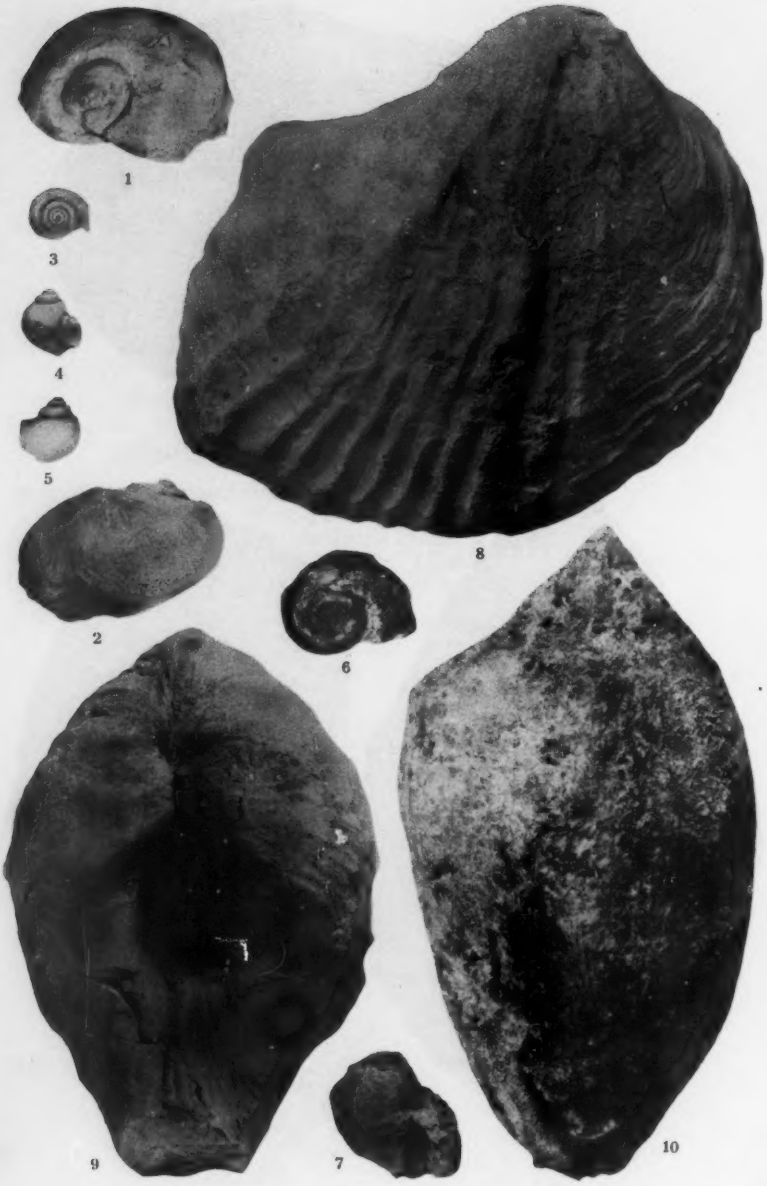
FOSSILS FROM THE DIFUNTA FORMATION



FOSSILS FROM THE DIFUNTA FORMATION

PLATE 16

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Gyrodes spillmani* Gabb
(Univ. Mich. 15078) Coll. 10.
FIGURES 3–5.—*Lunatia* cf. *rectilabrum* Gabb
(Univ. Mich. 15081) Coll. 30.
FIGURES 6, 7.—*Lunatia* sp.
(Univ. Mich. 15079). Float from Cerro El Pozo.
FIGURES 8, 9.—*Pholadomya kellumi* Imlay, n. sp.
Holotype (Univ. Mich. 14970) Coll. 1.
FIGURE 10.—*Lissapiopsis conica* Imlay, n. sp.
Back view of holotype (Univ. Mich. 15071) Coll. 16.
Figures natural size.

PLATE 17

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Lissapiopsis conica* Imlay, n. sp.
Front view of holotype (Univ. Mich. 15071) Coll. 16.
FIGURES 2, 3.—*Gyrodes* cf. *supraplicatus* (Conrad)
(Univ. Mich. 15089) Coll. 14.
FIGURES 4–6.—*Lissapiopsis unicarinata* Imlay, n. sp.
Holotype (Univ. Mich. 15067) Coll. 16.
Figures natural size.

FOSSILS FROM THE DIFUNTA FORMATION

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 18

FOSSILS FROM THE DIFUNTA FORMATION

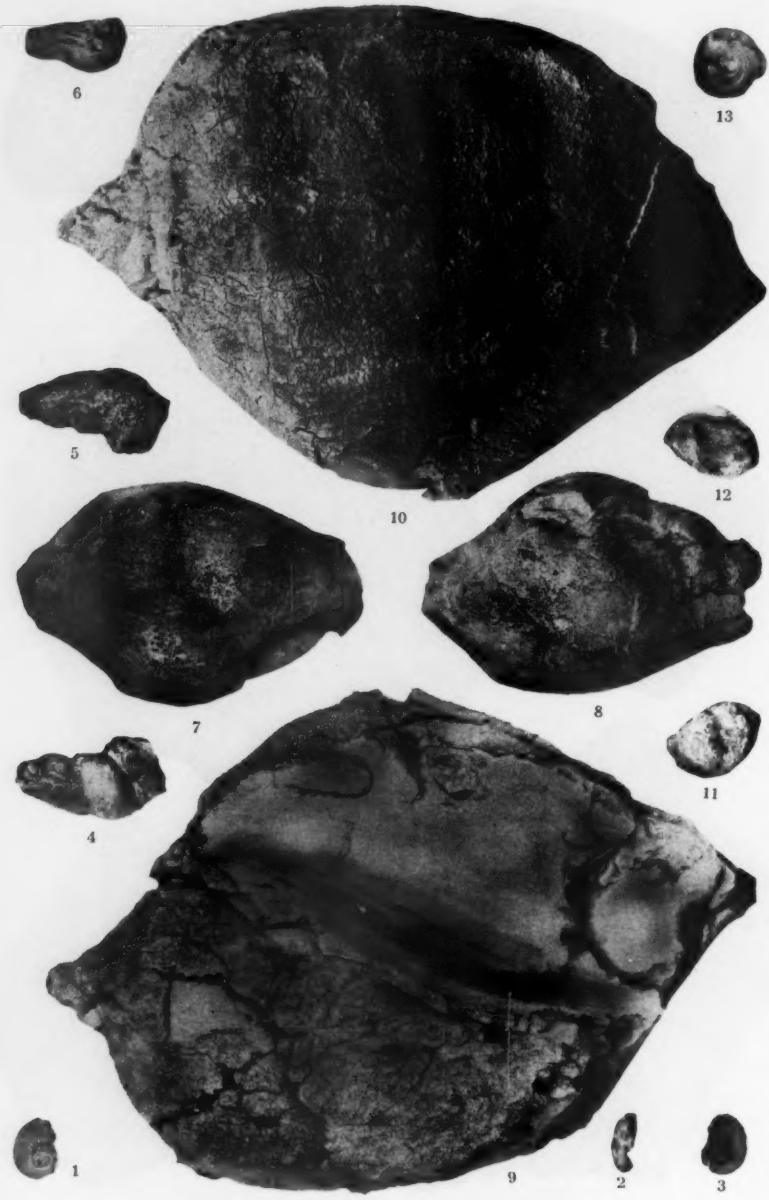
FIGURES 1–3.—*Gyrodes* cf. *supraplicatus* (Conrad)
Bottom, back, and top views (Univ. Mich. 15083). Found as float on Cerro El Pozo.
FIGURES 4–6.—*Strombus* (?) sp.
(Univ. Mich. 15090) Coll. 29.
Figures natural size.

PLATE 19

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1–3.—*Lissapiopsis inflata* Imlay, n. sp.
Holotype (Univ. Mich. 15065) Coll. 16.
FIGURES 4–6.—*Lissapiopsis simplex* Imlay, n. sp.
Holotype (Univ. Mich. 15072) Coll. 16.
Figures natural size.

FOSSILS FROM THE DIFUNTA FORMATION



FOSSILS FROM THE DIFUNTA FORMATION

PLATE 20

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1–3.—*Gyrodes* (?) sp.
Top, front, and bottom views (Univ. Mich. 15077) Coll. 30.
FIGURES 4–6.—*Anchura* (?) sp.
Figures 4, 5. Front and back views (Univ. Mich. 15100) Coll. 14.
Figure 6. Front view (Univ. Mich. 15101) Coll. 14.
FIGURES 7, 8.—*Volutilithes* (?) *arizpensis* Böse
(Univ. Mich. 15085). Float on Cerro El Pozo.
FIGURES 9, 10.—*Lissapiopsis apiculata* Imlay, n. sp.
Holotype (Univ. Mich. 15070) Coll. 16.
FIGURES 11–13.—*Lunatia* cf. *halli* (Gabb)
(Univ. Mich. 15080) Coll. 14.
Figures natural size.

PLATE 21

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Lissapiopsis tricarinata* Imlay, n. sp.
Holotype (Univ. Mich. 15068). Collected by native guide from Upper Cretaceous beds. Exact location unknown. Other view of holotype on Plate 22. Figures natural size.

2

1

FOSSILS FROM THE DIFUNTA FORMATION

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 22

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Lissapiopsis tricarinata* Imlay, n. sp.
Holotype (Univ. Mich. 15068). Other views on Plate 21.
FIGURES 3, 4.—*Pugnellus* (?) sp. c
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FIGURES 5–7.—*Pugnellus* (?) sp. a
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Top view of holotype (Univ. Mich. 15076) Coll. 16.
Figures natural size.

PLATE 23

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Paramorea* (?) sp.
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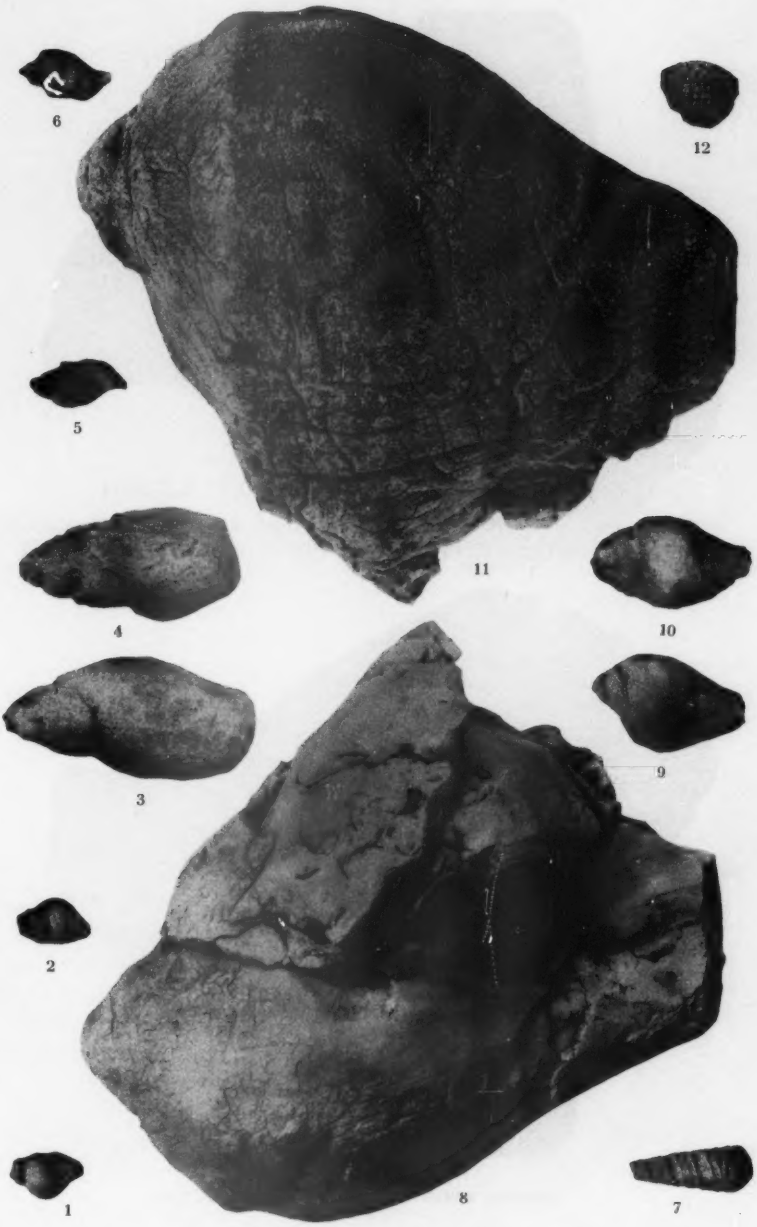
FIGURES 3, 4.—*Pugnellus* (?) sp. b
Figure 3. Back view (Univ. Mich. 15093) Coll. 14.
Figure 4. Back view (Univ. Mich. 15092) Coll. 14.
FIGURES 5, 6.—*Volutomorpha* (?) sp.
Front and back view (Univ. Mich. 15098) Coll. 30.
FIGURE 7.—*Turritella trilera* Conrad
(Univ. Mich. 15106) Coll. 14.
FIGURES 8, 11.—*Lissapiopsis bicarinata* Imlay, n. sp.
Front and back views of holotype (Univ. Mich. 15076) Coll. 16.
Top view on Plate 22.
FIGURES 9, 10.—*Pugnellus* (?) sp. d
Figure 9. (Univ. Mich. 15084) Coll. 5.
Figure 10. (Univ. Mich. 15086) Float on Cerro El Pozo.
FIGURE 12.—*Morea* (?) sp.
(Univ. Mich. 15102) Coll. 14.
Figures natural size.



FOSSILS FROM THE DIFUNTA FORMATION

2

1

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 24

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Lissiopsis gigantea* Imlay, n. sp.
Holotype (Univ. Mich. 15069) Coll. 16. Figures natural size.

PLATE 25

FOSSILS FROM THE DIFUNTA FORMATION

FIGURE 1.—*Lissapiopsis coahuilensis* Imlay, n. sp.
Holotype (Univ. Mich. 15066) Coll. 16.

FIGURES 2, 5.—*Lissapiopsis inflata* Imlay, n. sp.
Paratype (Univ. Mich. 15075). Found as float on north slope of Cuesta Difunta, about a quarter of a mile west of locality 18.

FIGURES 3, 4.—*Lissapiopsis inflata* Imlay, n. sp.
Paratype (Univ. Mich. 15074). Found as float on north slope of Cuesta Difunta about a quarter of a mile west of locality 18.

Figures natural size.

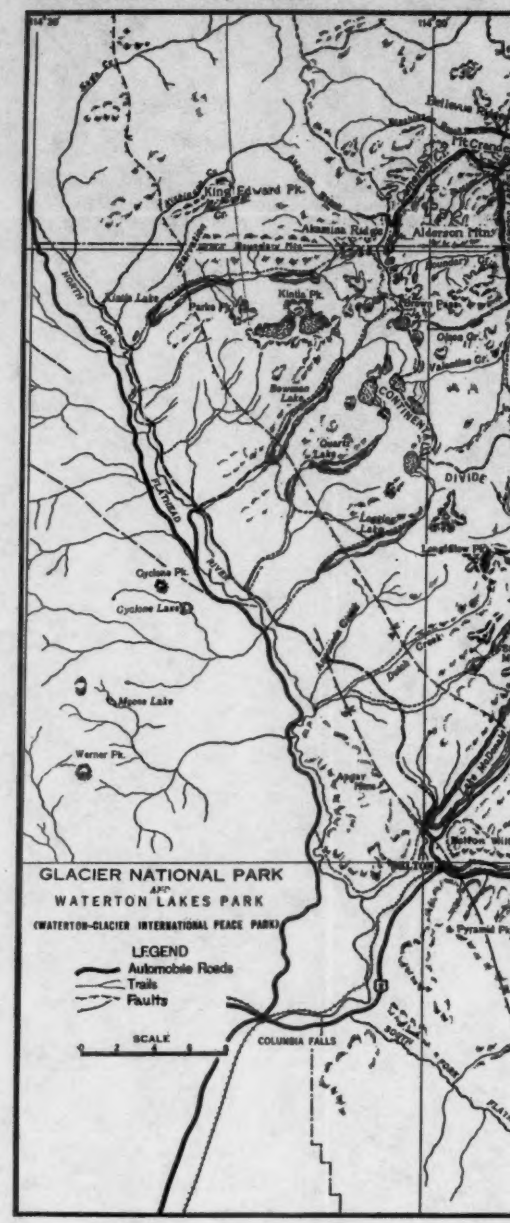
FOSSILS FROM THE DIFUNTA FORMATION

FOSSILS FROM THE DIFUNTA FORMATION

PLATE 26

FOSSILS FROM THE DIFUNTA FORMATION

FIGURES 1, 2.—*Lissapiopsis* sp.
(Univ. Mich. 15091) Coll. 15.
FIGURES 3, 4.—*Lissapiopsis simplex* Imlay, n. sp.
Paratype (Univ. Mich. 15073) Coll. 16.
Figures natural size.



MAP OF GLACIER AND WA
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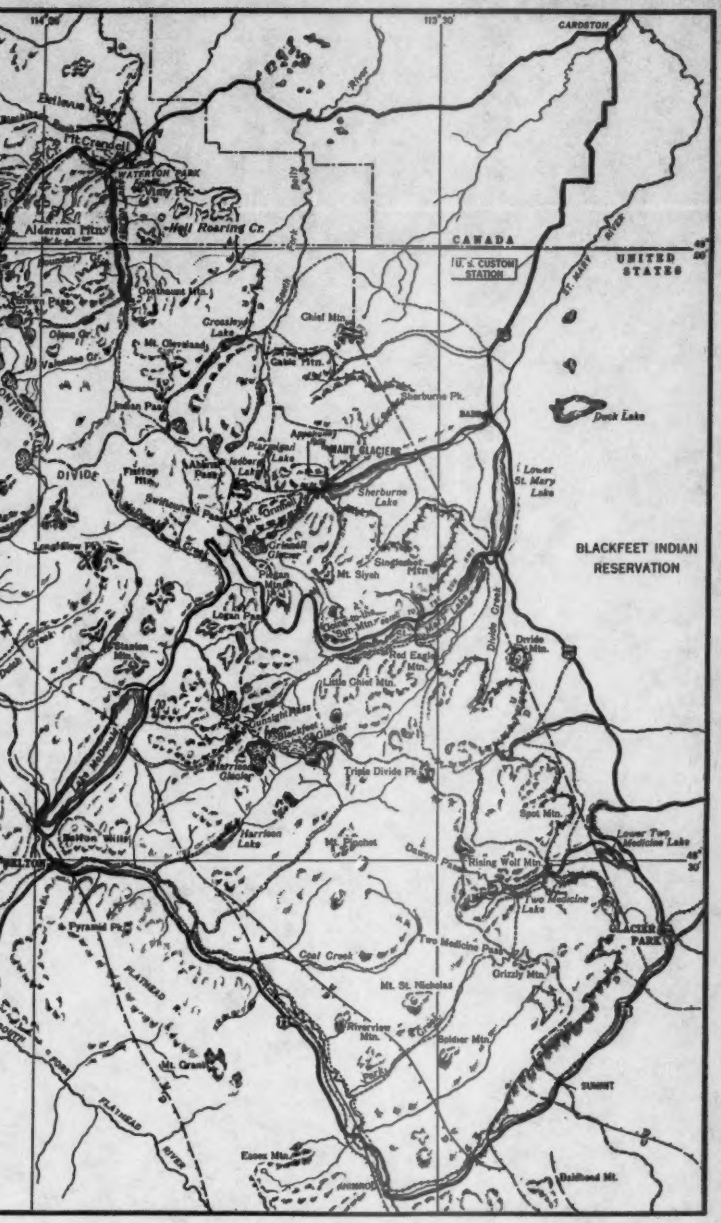

NER AND WATERTON LAKES NATIONAL PARKS
g physiographic features, roads and trails

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 48, PP. 1873-1970, 19 PLS., 20 FIGS. DECEMBER 1, 1937

BELT SERIES OF THE NORTH: STRATIGRAPHY, SEDIMENTATION, PALEONTOLOGY

BY CARROLL LANE FENTON AND MILDRED ADAMS FENTON

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INTRODUCTION

The writers' study of the Belt series began in 1927 and was continued in 1928 and 1932. Field work was virtually completed in 1934, when a grant from the Geological Society of America financed twelve weeks in Glacier and Waterton Lakes national parks and visits to other Belt outcrops. Further study of rhythmic sedimentation and algal deposits was permitted by a second grant from the Geological Society in 1936. The writers acknowledge their debt to the Society, to officials of the National Park Service, and to Dr. Charles Deiss, who lent specimens from Montana localities.

Collections of 1927 and 1928 are in the University of Cincinnati Museum; those of 1934 and 1936 were sent to Princeton University; specimens collected by Dr. Deiss are at the University of Montana. Series of metatypes have been placed in the Carnegie Museum, the Paleontological Museum of Oslo, the Naturhistorisches Museum, Vienna, and other institutions of North America and Europe.

THE BELT SERIES

NATURE, EXTENT, AGE

The Belt series, named by Walcott,[1] consists of clastic and non-clastic strata with minor lavas and intrusive rocks. It outcrops in Montana, Idaho, Alberta, British Columbia, northern Arizona, south-central Arizona, and southeastern California.[2] In its northern basin, the series

[1] C. D. Walcott: *Pre-Cambrian fossiliferous formations*, Geol. Soc. Am., Bull., vol. 10 (1899) p. 201.

[2] N. E. A. Hinds: *Uncompahgran and Beltian deposits in western North America*, Carnegie Inst. Washington, Pub. 463 (1936) p. 103-114, 129-131. This includes a review of earlier work on southern Beltian formations.

rests, in progressive overlap,[3] unconformably on Archean rocks; it is nonconformably overlain by the Middle Cambrian Flathead formation,[4] the erosion interval representing "orogenic and epirogenic movements which gently folded the Beltian deposits and elevated them more

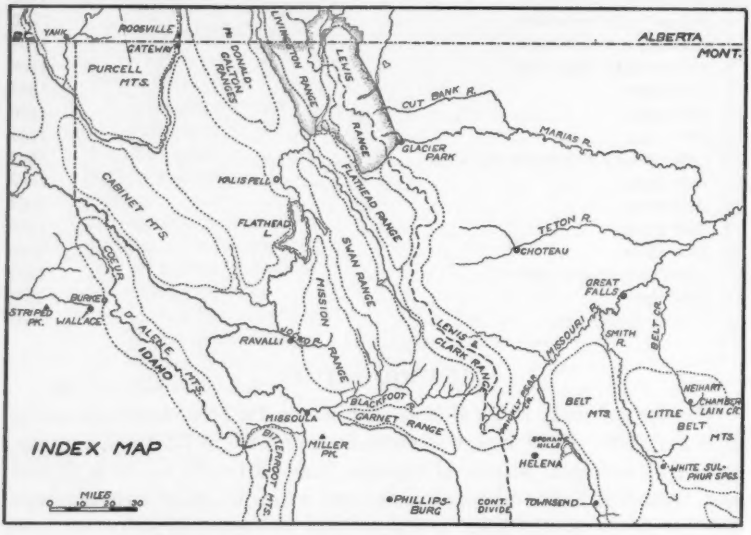

FIGURE 1.—*Index map of the northern Belt outcrop*
Stippled area includes Glacier and Waterton Lakes national parks.

than 20,000 feet into a mountainous mass . . . . Throughout subsequent Lipalian time these mountains were degraded at least 20,000 feet, terminating in a mature peneplain upon which the Middle Cambrian Flathead sandstone was deposited."[5] This peneplanation strongly supports Schofield's[6] conclusion that the Belt is pre-Cambrian, and negates the hypothesis[7] that the younger Belt sediments are of Lipalian (Penokean) age.

The fact that *Lingulella*, found in the Beltian Newland formation, also occurs in Cambrian strata does not conflict with this conclusion. Primitive genera occasionally survive from one era to another, as *Lingula*,

[3] C. D. Walcott: *Algonkian formations of northwestern Montana*, Geol. Soc. Am., Bull., vol. 17 (1906) p. 18.
C. H. Clapp and C. F. Deiss: *Correlation of Montana Algonkian formations*, Geol. Soc. Am., Bull., vol. 42 (1931) p. 690, 694.

[4] Charles Deiss: *Cambrian-Algonkian unconformity in western Montana*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 95-124.

[5] C. F. Deiss: *Cambrian-Algonkian unconformity in western Montana* (abstract), Geol. Soc. Am., Pr. 1933 (1934) p. 383.

[6] S. J. Schofield: *The Pre-Cambrian (Beltian) rocks of southeastern British Columbia and their correlation*, Geol. Surv. Canada, Mus. Bull. 2 (1914) p. 79-91; *Relationship of the Pre-Cambrian (Beltian) terrain to the Lower Cambrian strata of southeastern British Columbia*, Geol. Surv. Canada, Bull. 35 (1922) 15 pages.

[7] Charles Schuchert and C. O. Dunbar: *A textbook of geology*, pt. 2, 3d ed. (1933) p. 106.

Serpula, Apus, and *Limulus* prove. The index value of such a primitive genus as *Lingulella* surely is less than that of a nonconformity involving, on Newland Creek itself, all Beltian formations above the Spokane.

FACIES

Within its northern basin, the Belt series is divisible into facies [8] that differ in lithology, stratigraphic sequence, thickness, recorded conditions of deposition, fauna, and flora. Of these facies, six may be defined here; others probably will be distinguished in the future. Sections are given, in condensed form, in Figure 2.

1. MEAGHER FACIES. Includes the standard section of the series in the Belt Mountains and probably the Little Belt section; extends westward to Prickly Pear Creek. Distinguished by great thickness of the Spokane and presence of the Greyson member at its base. (Sections 11 and 12.)
2. BLACKFOOT CANYON FACIES. Characterized by development of Grinnell and Appekunny silt-clay argillites in place of the calcareous Chamberlain, and by great thickness of Siyeh, Spokane, and Sheppard or Helena, called "Upper Siyeh" by Clapp and Deiss. (Section 10.)
3. GLACIER PARK FACIES. Development of the series in Glacier National Park, Montana, Waterton Lakes National Park, Alberta, and westward to the Flathead trough. Grades into the dominantly clastic Purcell facies. (Section 6.)
4. GALTON FACIES. A transitional stage between the Glacier Park and Purcell facies. Distinguished from the former by more clastics in the Siyeh and Helena; from the latter by finer clastics below the Siyeh and presence of Altyn siliceous dolomites. (Section 5.)
5. PURCELL FACIES.[9] Marked by abundant clastics throughout, with reduction of carbonate rocks. Quartzites, thick in lower portions, reach the known base of the Belt. (Section 4.)
6. COEUR D'ALENE FACIES. Closely related to the Purcell. Characterized by sandstones and argillaceous beds throughout the Striped Peak (= lower Spokane), by reduction of carbonate rocks in the Siyeh equivalent (lower Wallace), and by tripartite division of the Ravalli, which is clastic throughout. (Section 1.)

In Figure 2, named formations and members of the Belt facies are correlated within the Belt basin. This correlation is based on the writers' conclusion that "Hole-in-the-Wall" argillites [10] of the Glacier Park facies are Spokane in age. Clapp and Deiss [11] first assigned equivalence to the Newland and the Siyeh formations and recognized a thick group of clastic formations above the Helena (=Sheppard, Gateway).[12] Differences between the Clapp and Deiss table and that of Figure 2 chiefly involve new conclusions regarding equivalence of formations above the Spokane and of pre-Siyeh formations in the Purcell facies.

[8] C. L. Fenton and M. A. Fenton: *Ecologic interpretations of some biostratigraphic terms,* Am. Midl. Nat., vol. 12 (1930) p. 147-149.

[9] Galton and Purcell facies are those "series" of Daly and Schofield; the Glacier Park corresponds roughly to Daly's Lewis "series." Because of the associated Lewis thrust, application of this name to strata seems inadvisable.

[10] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park,* Jour. Geol., vol. 39 (1931) p. 673. "Hole-in-the-Wall" is here suppressed in favor of Spokane.

[11] C. H. Clapp and C. F. Deiss: *op. cit.,* p. 673-695; fig. 3.

[12] For a summary of correlations by Walcott, Calkins, Daly, and Schofield, *see* S. J. Schofield; *The pre-Cambrian (Beltian) rocks of southeastern British Columbia and their correlation,* Geol. Surv. Canada, Mus. Bull. 2 (1914) p. 79-91.

FIGURE 2.—*Correlation table of Belt formations and members*

PART I. STRATIGRAPHY

STANDARD SECTION

In this paper, formations of the Glacier Park facies are taken as standard, because they are most easily available and best known, as well as the chief subjects of the writers' field work. They outcrop principally in the Lewis and Livingston ranges of Glacier National Park, Waterton Lakes National Park, and southeastern British Columbia. First described by Dawson [13] and Bauerman,[14] they remained almost unknown until Willis,[15] assigning them to the Algonkian, named their chief stratigraphic units and described their structure. In 1906, Walcott [16] assigned part of their strata to the Cambrian and Ordovician; in 1913, Daly [17] placed all except the basal formation in the Cambrian but used Willis' names and proposed new ones for closely related formations to the westward. Later authors have followed Willis, recognizing new stratigraphic units both within and above those he mentioned.

The eastward boundary of the Glacier Park outcrop [18] is the Lewis thrust; as mapped by Clapp,[19] the southwesterly and westerly borders are normal faults; the northern boundary has not been determined. Within this thrust-block the structure was described by Willis as an easterly monocline (Lewis Range), a central syncline (Waterton-McDonald Valley) and a westerly anticline (Livingston Range). In the first and second divisions the strata commonly approach horizontality, though their structure is more complicated than some writers have assumed. The Lewis thrust itself is complex, both obscuring and repeating substantial thicknesses of strata. A major subsidiary fault eliminates the upper (Carthew) member of the Altyn formation from Yellow Mountain southward, although on Vimy Peak, in Waterton Lakes Park, that division is thickened by repetition of sandstones and is thrust over crumpled Appekunny argillite. Near Logan Pass, the crest of the Lewis Range is part of a monocline; at Gunsight Pass, 6.5 miles southward, it is a steep anticline whose axis is exposed in Avalanche Cirque. Fold-

[13] G. M. Dawson: *Report on the geology and resources of the region in the vicinity of the forty-ninth parallel from the Lake of the Woods to the Rocky Mountains*, Brit. N. A. Boundary Comm. (1875) p. 67-68. Dawson assigned the strata to Cambrian and younger systems.

[14] Hilary Bauerman: *Report on the geology of the country near the forty-ninth parallel of north latitude west of the Rocky Mountains, from observations made in 1859-61*, Geol. Surv. Canada, Rept. Prog. 1882-83-84 (1885) B, p. 1-41.

[15] Bailey Willis: *Stratigraphy and structure, Lewis and Livingston ranges, Montana*, Geol. Soc. Am., Bull., vol. 13 (1902) p. 305-352.

[16] C. D. Walcott: *op. cit.*, p. 13, 14, 22.

[17] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Canada Dept. Int., Rept. Chief Astronomer, vol. 2 (1913) p. 178 a, 189; Geol. Surv. Canada, Mem. 38 (1912?).

[18] Topographic maps: *Glacier National Park, Montana*, U. S. Geol. Surv. or Nat. Park Service; *Waterton Lakes Park*, Topog. Surv. Canada or Nat. Parks Canada.

[19] C. H. Clapp: *Geology of a portion of the Rocky Mountains of northwestern Montana*, Mont. Bur. Mines Geol., Mem. 4 (1932) pl. 1.

ing is abrupt on Heavens Peak, near the south end of the Livingston Range; near Brown Pass it is gentle; near Waterton Park the mountain front is intensely folded and faulted. Low-angle thrusts cut monoclines in the Lewis Range, repeating or eliminating many strata.

RAVALLI GROUP

DEFINITION: Dominantly clastic rocks which form the lowest major division of the Belt series in the Meagher, Blackfoot Canyon, Glacier Park, and Galton facies, but are underlain by the Prichard clastics in the Purcell facies.[20] In the Glacier Park facies, they include the semi-clastic and carbonate Altyn formation, which presumably grades westwardly into clastics. Thickness 7800 to 15,000 feet.

TYPE LOCALITY: Hills along the Jocko River, near Ravalli, Montana.

DISCUSSION: Walcott[21] applies the term Ravalli to 8255 feet of sandstone which includes equivalents of both the Appekunny and Grinnell of Waterton-Glacier parks, though he also includes Spokane clastics. Clapp and Deiss,[22] quoting Wilson, list 10,700 feet of Ravalli quartzites and argillites in the Mission Range and limit the group as it is here defined. Clapp[23] maps the group, giving the following section:

Ravalli group

	Feet
GRINNELL FORMATION. Red with some green argillite, sandstone, and sandy quartzite	2000– 3500
APPEKUNNY FORMATION. Green-gray to light- or dark-gray argillitic and sandy quartzite and quartzitic argillite; some massive whitish quartzite	3500–10,000
ALTYN FORMATION. Impure, siliceous, argillaceous to sandy or pebbly limestone, with beds of calcareous, pebbly sandstone. Not exposed west of the continental divide	1400

These divisions, the lowest in greater thickness, are found in the Glacier Park facies. The basal Ravalli in the Little Belt Mountains consists of pinkish quartzite (Neihart) about 700 feet thick. Above it lies the Chamberlain "shale," to which Weed[24] assigns a thickness of 2078 feet, though Walcott[25] apparently places 578 feet of the uppermost gray, non-massive shale in the Newland formation, reducing the Chamberlain to 1500 feet.

Chamberlain strata grade into Newland near Little Birch Creek, in foothills of the Belt Range. Quartzite beds, however, are much thicker than those recorded on Belt Creek; they rise high on slopes and are folded into granitic rocks almost to the crest of the range. Characteristically, they are thinly bedded, blue-green, hard, and micaceous. Gray, greenish, and reddish argillites are interbedded with them. The thickness, below limy Newland shales, is estimated at 1750 feet.

[20] Definitions of stratigraphic names and units not marked new are emended.

[21] C. D. Walcott: *Algonkian formations of northwestern Montana*, Geol. Soc. Am., Bull., vol. 17 (1906) p. 7.

[22] C. H. Clapp and C. F. Deiss: *Correlation of Montana Algonkian formations*, Geol. Soc. Am., Bull., vol. 42 (1931) fig. 3.

[23] C. H. Clapp: *op. cit.*, p. 22.

[24] W. H. Weed: *Geology of the Little Belt Mountains, Montana*, etc., U. S. Geol. Surv., 20th Ann. Rept., pt. 3 (1900) p. 283-284.

[25] C. D. Walcott: *Pre-Cambrian fossiliferous formations*, Geol. Soc. Am., Bull., vol. 10 (1899) p. 206, 209.

Cliffs of Blackfoot Canyon show red, green, and (dominantly) purplish argillites and quartzites, divisible into a lower member 2400 feet thick and an upper member 2600 feet thick. Clapp and Deiss[26] correlate these members with the Appekunny and Grinnell formations of Glacier Park, which, in turn, may be correlated with the green and purple, dominantly quartzitic beds near Ravalli. Bedding is more massive than in the Meagher facies, and there is more quartzite and less gray to black shale.

In the Galton facies, Daly[27] distinguishes four formations, which he tentatively correlates with the Ravalli of the Glacier Park facies. Despite the uncertainty of long-distance correlations of the Belt, the writers derive this section from Daly's description:

	Feet
WIGWAM FORMATION (Grinnell)	
5. Sandstones, thinly bedded, red to red-brown, with partings of red siliceous argillite and interbeds of brown argillite and red grit. Mud cracks, ripple marks and cross-bedding abundant	1200±
MACDONALD FORMATION (Appekunny)	
(Scenic Point member)	
4. Argillite; weathers gray, brown, or buff; interbeds of red sandy or argillaceous strata and dolomites, 3 to 6 inches thick, bearing abundant flattened "concretions" *(Collenia?)*	700
(Appistoki member)	
3. Argillite; weathers light-gray; one band of red shale, 60 feet thick, and a thin magnesian oölite bed, 500 feet above base	1100±
2. Argillite; weathers light-brown to brownish gray	550
HEFTY FORMATION (Singleshot member)	
1. Sandstone, thinly bedded, red to reddish gray, interbedded with thin strata of red shale and greenish gray quartzites. Mud cracks and ripple marks common	775
ALTYN FORMATION (Carthew? member)	
Dolomites, siliceous, thinly bedded	650
	4975±

ALTYN FORMATION

DEFINITION: Dolomites, limestones, limy argillites, sandstones, and minor mud breccias which form the lower calcareo-magnesian division in the Belt sediments of the Glacier Park facies. The sediments show considerable variety in color, texture, and bedding; they contain mud cracks, ripple marks, and many beds of flat-pebble and edgewise conglomerates. Their upper limit is the base of the Appekunny, with which they show some intergradation; their lower limit is concealed beneath the Lewis thrust. Thickness, 2180 to 2480 feet.

TYPE LOCALITY.—Cliffs at the foot of Appekunny Mountain, about a mile northeastward from Swiftcurrent Falls, Glacier National Park. Entire section exposed only in Waterton Lakes Park, where it is complicated by faults and folds.

DISCUSSION: This definition includes the Altyn of Willis[28] and Daly's Waterton

[26] C. H. Clapp and C. F. Deiss: *op. cit.*, p. 693, fig. 3.

[27] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 97-104.

[28] Bailey Willis: *Stratigraphy and structure, Lewis and Livingston ranges, Montana*, Geol. Soc. Am., Bull., vol. 13 (1902) p. 317, 321.

formation,[20] for no significant break exists between them, and Daly himself emphasizes their conformability.

The Carthew member occurs only north of the Swiftcurrent Valley. Near Many Glaciers the basal Appekunny rests upon the Hell Roaring member. Between them lies Willis'[20] "second Lewis thrust," which cuts progressively older Altyn strata and removes the Carthew in the region between Yellow Mountain and Marias Pass. There, it cuts lower and lower strata, although the main Lewis thrust rises until, on the western cliffs of Summit Mountain, the Altyn either becomes a series of thin wedges or terminates, leaving the Appekunny in contact with the folded and faulted Cretaceous strata.

Waterton Member.

DEFINITION: Dolomites, dark-gray and reddish, weathering to gray, reddish brown and buff, in beds 1 to 4 feet thick.[21] Most beds are finely laminated, laminae numbering 10 to 60 per inch. No sand grains were noticed. Some strata suggest thickly bedded, limy argillites. Daly's analysis shows 28.60 per cent calcite, 21.17 per cent magnesium carbonate, and 34.47 per cent orthoclase.

The member grades upward into dolomites of the Hell Roaring member; its base is not visible; its known thickness is about 280 feet.

TYPE LOCALITY: Cliffs at Cameron Falls on Cameron ("Oil") Creek, near Waterton Park.

DISCUSSION: At its type locality, the Waterton forms the core of an anticline trending eastward along Cameron Creek. Thrusting and folding expose it above Hell Roaring Falls, near the east shore of Waterton Lake, where the estimated thickness is 280 feet. Thick bedding, pseudo-argillitic appearance, and dull reddish laminae are conspicuous. A boring near Cameron Falls shows 1500 feet or more of "limestones" and "argillite," many of which Daly[22] found to be "similar to common phases of the Waterton." They may belong to it, but, since fault wedges of Appekunny penetrate the Altyn on Mt. Crandell and beneath the plains, the argillites may be Appekunny, while some limestones may belong to Hell Roaring and Carthew members of the Altyn formation. No ripple marks, argillites or fossil algae have been found.

Hell Roaring Member (nov.)

DEFINITION: Dolomite and dolomitic limestones, variably siliceous; blue-gray to greenish gray, weathering to gray, buff, or cream; beds 2 to 24 inches thick. Many beds show laminae of limestone and dolomite and apparently primary dolomite nodules, associated with biostromes of *Collenia albertensis* n. sp. Thickness estimated at 1200 to 1300 feet.

TYPE LOCALITY: Hell Roaring Falls, Waterton Lakes Park. Well exposed on the eastern slope of Mt. Carthew.

DISCUSSION: This is the "lower member" of Willis' Altyn descriptions. It seems also to include the basal members (f, g) of Daly's section,[23] described as gray to greenish-gray magnesian limestones bearing cherty nodules and siliceous concentric concretions. The latter probably are *Collenia albertensis* n. sp., which is found near the eastward bend of Cameron Creek, along the trail near the eastern foot of Mt. Carthew, north of the mouth of Hell Roaring Canyon, and on the northern

[20] R. A. Daly: *op. cit.*, p. 50.
[20] Bailey Willis: *op. cit.*, p. 334-335.
[21] R. A. Daly: *op. cit.*, p. 54.
[22] *Op. cit.*, p. 55.
[23] *Op. cit.*, p. 56.

slope of Gable Mountain. In the second and last of these localities, its laminae are cherty.

The Hell Roaring-Waterton contact is marked by change from dull red to blue-gray, thinning of beds, and diminution of dolomite, which alternates with limestone. Where it can be found, *Collenia albertensis* n. sp. is an index fossil. A few beds of reddish-brown dolomite, 1.5 to 12 feet thick, are exposed in some sections, but are fewer than those of the overlying Carthew formation.

On Cameronian Mountain and Cameron Creek, low-angle faults give the Hell Roaring member an apparent thickness of 1800 feet. Recognizable repetitions reduce this to 1400 feet, with virtual certainty of further duplication by low-angle thrusts, not recognizable along the strike. The estimate of 1300 feet probably is within the range of actual fluctuation in thickness, and allows for beds lower than any seen on the northern slope of Gable Mountain and the base of Chief Mountain, where Willis estimated 800 feet of markedly siliceous strata.

At Mt. Appekunny, the type locality of the Altyn, the uppermost Hell Roaring beds are massive, light-gray, dolomitic limestones interbedded with edgewise mud breccias and lenses of dolomitic sandstone or conglomerate; their thickness averages 85 feet. Massive beds are crowded with *Collenia columnaris* Fenton and Fenton, an alga closely resembling *C. albertensis* n. sp. in section, but with different growth-form and habits. They form the Collenia columnaris zone.

Above this zone, between Appekunny and Swiftcurrent Falls, gray dolomitic limestones which split into fine laminae bear the carbonaceous films described as *Beltina* and *Morania antiqua* n. sp. Lower strata of the Morania zone, bearing symmetrical ripple marks 2 to 3 inches in amplitude, are best exposed near Swiftcurrent Creek. The total thickness of the Morania zone approximates 225 feet, in keeping with the "at least 200 feet" through which Daly[84] found *"Beltina"* in Cameron Valley, Waterton Lakes Park.

Pebbly and sandy dolomites overlie the Morania zone and form the cliff at Appekunny Falls. They contain isolated colonies of *Collenia columnaris* Fenton and Fenton.

Near Roes Creek, in the St. Mary Valley, the uppermost Altyn consists of similar massive, buff-weathering, sandy dolomites containing semi-rounded and angular pebbles, 2 to 15 millimeters in diameter; some beds contain strong, symmetrical ripple marks. Below these are thick gray beds; both are exposed in complex fault wedges which form the ridge called the Golden Stairs. At its foot, near Roes Creek Falls, there is 4 to 20 feet of the flaggy beds of the Morania zone, containing characteristic carbonaceous fossils.

On Divide Mountain, south of St. Mary Lake, about 1200 feet of buff-weathering, gray dolomites and limestones show little faulting. The Altyn thickness of 1400 feet given by Clapp[85] represents the Hell Roaring member only; determined on the north side of the Cut Bank Valley, it contains few repeated beds. In the Two Medicine Valley, at least 200 feet of massive, siliceous, sand- and pebble-bearing dolomites is folded and faulted. Pebbles are as much as 20 millimeters in diameter; algae are small and sparsely distributed.

Carthew Member (nov.)

DEFINITION: Magnesian limestones, dolomites, quartzites, and intermediate rocks which grade upward into the basal Appekunny. Colors range from blue-gray through

[84] *Op. cit.*, p. 65.

[85] C. H. Clapp: *Geology of a portion of the Rocky Mountains of northwestern Montana*, Mont. Bur. Mines Geol., Mem. 4 (1932) p. 22.

buff to brown and dark brownish red; bedding is thin to thick. Red beds, especially, show thin laminae. Thickness is estimated at 700 to 900 feet.

TYPE LOCALITY: Eastern cliffs of Cameronian Mountain above Cameron Creek, Waterton Lakes Park. Well exposed on the eastern face of Bertha Mountain, on slopes between Vimy Peak and the Narrows of Waterton Lake, and on the northern cliffs of Gable Mountain, Glacier National Park.

DISCUSSION: In Waterton Lakes Park, this member of the Altyn formation is lighter colored than farther south and contains a greater proportion of clastic material. Between the Narrows and Vimy Peak, the following section is exposed:

	Feet
10. Limestone, in beds 9 to 15 inches thick; magnesian, fine-grained, gray; weathers light blue gray, whitish, or buff. Many structureless chert nodules	300±
9. Sandstone and quartzite, massively bedded; white or light-gray, weather brownish. Uppermost beds contain coarse, angular sand grains; lenses of coarse sand are exposed below, though the bulk of the rock is fine grained. Much crumpled and faulted in lowermost beds. Estimated thickness	200
8. Dolomite, medium-bedded, siliceous, gray; weathers yellow-buff; interbedded with thin gray shaly layers. Folding and faulting complex. Estimated thickness	35
7. Dolomite, like No. 5, interbedded with red dolomitic argillites, 1 to 3 feet thick. Upper layers crumpled and faulted. Estimated thickness	15
6. Dolomite, thinly bedded, laminated, brick-red	35
5. Dolomite, cross-bedded, finely laminated; red to purplish; weathers to brown blocks	16
4. Limestone, thickly bedded, fine-grained, dolomitic, much broken. Dark pinkish, gray, weathers buff	13+
3. Dolomite, cross-bedded, finely laminated, brownish red	11
2. Limestone and dolomite, thinly to thickly bedded; gray, weather buff. Contains sandy lenses and much edgewise conglomerate	67±
1. Dolomite, medium-bedded, gray; weathers buff; poorly exposed. Estimated thickness	200
	892±

On the south face of Mt. Crandell, Nos. 9 and 10 form a complex of fault wedges. The sandstone (No. 9) lies in its normal position and is repeated six times in wedges, with a total thickness approximating 1400 feet. On Cameronian Mountain, Carthew sandstones are repeated; three main and several minor thrust wedges also repeat the limestones of No. 10 until they seem to be 1250 or 1300 feet thick. In places, however, beds belonging to Nos. 1 and 2 are hidden, so that they persist on Mt. Crandell only as crumpled wedges between faults.

On Gable Mountain, the sandstones are represented by white, sandy dolomites. Reddish-brown to purple, laminated dolomites are prominent; below them are limestones which weather blue gray. As repeated by oblique thrusts, these colors give an appearance of red, white, and blue diagonal bands. Faults are reduced in number on the upper part of Chief Mountain, though many oblique faults cut its lower mass.

Between the Galton and Purcell ranges, the Glacier Park facies terminates, and boundaries of the Ravalli group become obscure. The Creston formation, as de-

scribed by Daly[36] and revised by Schofield,[37] consists of 5000 feet of grayish quartzites, argillaceous quartzites, and argillites, in beds approximately a foot thick. Textures are coarse in eastern but fine in western exposures. Near Coeur d'Alene, the Creston is replaced by the Burke, Revett and St. Regis formations, described by Calkins[38] as sandstones, shales, quartzitic sandstones, and quartzites, dominantly gray and purplish basally, but green and purple in the upper 800 feet (St. Regis). They cannot be correlated with formations in the Glacier Park facies.

APPEKUNNY FORMATION

DEFINITION: Argillite interbedded with quartzite, conglomerate, and minor beds of argillaceous limestone; prevailingly green, greenish-gray to brownish, with some dull red, white, and purplish beds. Thin-bedded to thick-bedded, with fine laminae; massive only in quartz conglomerates and quartzites. Grades into adjacent formations. In its eastern phases, the thickness is 2500 to 5300 feet; in western,[39] it is as much as 10,000 feet.

TYPE LOCALITY: Appekunny Mountain, north of Swiftcurrent Valley, Glacier National Park.

DISCUSSION: The formation as here defined excludes the Rising Wolf member, which the writers at first placed in it.[40] The upper boundary of the Appekunny, therefore, is drawn at the top of the zone of purplish, red, flesh, and dull-brown beds or their equivalents, and below those dominantly white and red.

In the Two Medicine area, the middle (Appistoki) beds are largely greenish brown, but the upper (Scenic Point) are red, brown, and purplish. Mud cracks, ripple marks, and argillaceous breccias are found in all, but are especially abundant in transition members. Northward from the Two Medicine Valley, the Appekunny shows increased thicknesses of red argillites in both upper and lower members, a general increase in mud breccias throughout the formation, and diminution of coarse clastics in the upper (Scenic Point) member. Red beds are exposed in the upper and lower beds near Many Glaciers, but the thick middle member is green. Red beds occur throughout the formation in Bellevue Hill, Waterton Lakes Park; the basal member becomes markedly sandy in the Galton Range.

Near Ravalli, the Appekunny consists chiefly of purplish and gray-green quartzites and siliceous argillites, not readily distinguishable from the overlying Grinnell.

Singleshot Member.

DEFINITION: Argillites and quartzites, interbedded with buff to greenish siliceous dolomite and dolomitic sandstone. Pelitic rocks are gray, gray green, reddish, and black; quartzites are greenish, pink, or white. Mud cracks, ripple marks, and mud breccias are abundant. In some places, a basal coarse, pinkish sandstone rests on the Altyn with slight angular unconformity. Thickness, 300 to 400 feet.

TYPE LOCALITY: Singleshot Mountain near St. Mary Lake, Glacier National Park.

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[36] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 120-122.

[37] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) p. 23, 28-31.

[38] F. C. Calkins *in* F. L. Ransome and F. C. Calkins: *The geology and ore deposits of the Coeur d'Alene district, Idaho*, U. S. Geol. Surv., Prof. Pap. 62 (1908) p. 24-39.

[39] C. H. Clapp: *Geology of a portion of the Rocky Mountains of northwestern Montana*, Mont. Bur. Mines Geol., Mem. 4 (1932) p. 22.

[40] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 675.

DISCUSSION: West of Waterton Lake, the Singleshot includes the two lowest members of Daly's general Appekunny section:[41]

	Feet
2. Dolomite, siliceous, thin- to medium-bedded; weathers buff	75
1. Argillite and quartzite, which weather brown, red and gray; sparsely interbedded with buff dolomitic sandstone and grit; mud cracks and ripple marks common	300

This dolomitic phase is best developed in the lower valley of Cameron Creek. On Vimy Peak, east of Waterton Lake, the Singleshot contains much rose-red argillite, as it does on Bellevue Hill and Lakeview Ridge, north of Blackiston Valley. Approximately 400 feet of red, brown, and greenish argillites is exposed on the western slope of Goathaunt Mountain and on the northern face of Gable Mountain; on the latter, there are white quartzite bands and few red strata. These quartzites thicken on Appekunny Mountain, follow the face of East Flattop, and reach their maxima in the type exposure on Singleshot Mountain, where the red argillites are further reduced; they are nearly absent from the Two Medicine region, where the thickest quartzite bed measures less than 40 feet.

In the Galton Range, Daly found 775 feet of sandstone, shale, and quartzite (Hefty) whose position and lithology suggest that they are a coarser phase of the Singleshot.

Appistoki Member.

DEFINITION: Gray, green, olive-brown, and rusty-gray argillites in thin minor but thick major beds, interbedded with thickly stratified, greenish, white, or pink quartzites. Flat-pebble breccias, mud cracks, and ripple marks are abundant; rain and sleet prints are present in some layers. This member intergrades with other members, yet preserves fairly well-marked limits. Thickness in the Lewis Range, 2000 to 2200 feet.

TYPE LOCALITY: Appistoki Peak, near Two Medicine Lake, Glacier National Park.

DISCUSSION: In western cliffs of the Livingston Range, the Appistoki consists of alternating thinly bedded, gray-green argillites and quartzites interbedded with white and iron-stained quartzites. Eastward, all quartzites diminish in thickness; argillites, though siliceous, are not coarsely gritty, and the dominant colors are bluish green and gray.

In the Two Medicine region, the Appistoki consists primarily of finely laminated argillites; the more siliceous layers are united in beds 10 to 20 inches thick which contain 2 to 22 laminae per centimeter. Mud cracks and flat-pebble breccias are found throughout the member, especially in mountains surrounding the Swiftcurrent Valley. Pebbles are typically small and blue green, and are embedded in a darker-green, gritty matrix. Ripple marks are few and are generally obscured by slipping of adjacent beds. Thin, highly micaceous strata are considerably metamorphosed.

Scenic Point Member (nov.)

DEFINITION: Argillites, sandstones, and gravelly conglomerates; green, purplish, buff, brown, and dull brownish-red at the type locality. Northward and westward from the type locality, the member grades into thickly bedded, coarsely mud-cracked argillites, which give way to thick quartzites and subordinate gray and

[41] R. A. Daly: *op. cit.*, p. 67.

iron-stained argillites. Mud breccias, mud cracks, and ripple marks are abundant. Thickness, 200 to 700 feet.

TYPE LOCALITY: Scenic Point, overlooking Two Medicine Valley, Glacier National Park.

DISCUSSION: To this member, the writers assign 200 feet[42] of thickly bedded quartzite and interbedded gray to rusty argillite, as well as 75 to 100 feet of subjacent coarsely mud-cracked argillites and quartzites, exposed in the western part of the Livingston Range; to the eastward, the quartzites become thin and fine-grained or give way to red argillites. On Vimy Peak, at the northern end of the Lewis Range, there are about 400 feet of red and green argillites.

The Scenic Point member, near Many Glaciers, consists of thickly bedded, coarsely mud-cracked argillites, green or purplish-green, with a few dull, dark-red interbeds. They form resistant ledges near lakes and streams. Still more massive ledges outcrop beside St. Mary Lake.

In the Two Medicine Valley, the Scenic Point member forms cliffs at Twin Falls and below Upper Two Medicine Lake. Its heavy ledges are exposed along the trail to Cobalt Lake; they are blue green and contain 4 to 10 laminae per cm. Mud cracks, 6 to 50 mm. wide, enclose nearly flat polygons whose dimensions reach 15 by 40 cm. The uppermost argillites are interbedded with purplish or red flat-pebble breccias and thin, brownish quartzites.

At the type locality, the Scenic Point member contains micaceous to earthy, green, red, buff, and brown argillites. Earthy argillites are interbedded with coarse, friable sandstones, many of which fill mud cracks or overlie argillites whose laminae are pitted by sand. Mud-crack polygons range from flat to convex. Definite rain prints have not been observed.

Fossils are unknown in the Scenic Point member of Waterton-Glacier Parks, but Daly[43] mentions concentrically laminated "concretions"—probably *Collenia*—in the upper MacDonald (Appekunny) formation of the Galton Range.

GRINNELL FORMATION

DEFINITION: Red or purplish argillites and white to light-green quartzites, lying between the Appekunny and the succeeding Piegan group. Textures, colors, and bedding are highly variable; ripple marks, mud cracks, and current marks are abundant, as are rain or hail prints in some members. Thickness, 1500 to 3500 feet.

TYPE LOCALITY: Grinnell Point (Stark Point of some maps), at the head of Swiftcurrent, formerly McDermott Lake.

DISCUSSION: On King Edward Peak, west of Waterton Lakes Park, Daly[44] distinguished the following five divisions of the Grinnell:

	Feet
5. Argillite, thinly bedded, red, interbedded with some red, quartzitic sandstone	355
4. Lava, basic, amygdaloidal	20
3. Argillite, thinly bedded, red	75
2. Quartzite, argillaceous, thinly bedded, gray; weathers light, rusty brown	100
1. Argillite, thinly bedded, red to reddish-gray, and quartzitic sandstone	1050
	1600

[42] *Op. cit.*, p. 67.
[43] *Op. cit.*, p. 101.
[44] *Op. cit.*, p. 70.

In Blackiston Valley, in Waterton Lakes Park, thicknesses are variable. A series of sections show:

	Feet
RISING BULL MEMBER	
5. Argillite, thinly bedded, red, interbedded with white quartzites and quartzitic mud breccias. Ripple marks and mud cracks abundant	380
4. Lava, massive, amygdaloidal, with indistinct ellipsoids; greenish...	22– 35
3. Argillite, red, interbedded with greenish and white quartzites; much like No. 5	140±
RED GAP MEMBER	
2. Argillite, thinly bedded; red with some green beds. Many minor beds of white to brownish quartzite. Mud cracks numerous; enclosing flat secondarily cracked polygons. Ripple marks and flat-pebble breccias common	700–800
RISING WOLF MEMBER	
1. Argillite, thinly bedded, sandy, red to brownish, interbedded with white, greenish, and brownish quartzites. Coarse mud cracks, ripple marks, and edgewise mud breccias abundant	250–300
	1600±

On Cameronian Mountain, the Grinnell forms steep cliffs. No lava is found, and there is little difference between the equivalents of Nos. 1 and 2 of the Blackiston Valley sections. The total thickness is 1500 feet or less.

Amygdaloidal lava is not exposed in sections south of the International Boundary. Argillites and quartzites thicken; Pass Creek, below Indian Lake, crosses at least 2400 feet of Grinnell, with an uppermost zone of white quartzites and red argillites, about 500 feet thick, and with the base concealed by drift. At Ptarmigan Wall, many quartzites and argillites are green. In this region, there is an upper quartzitic zone about 1100 feet thick, a middle argillitic one 1800 feet or more thick, and a basal 500 feet of green to white quartzite and interbedded red argillite. These the writers[45] have named the Rising Bull, the Red Gap, and the Rising Wolf members, respectively.

Southward from Ptarmigan Wall, the Grinnell thins, due chiefly to reduction of the argillaceous Red Gap. On Mt. Grinnell the total thickness is about 2200 feet; on Rising Wolf, near Two Medicine Lake, it is less than 1800 feet, and on Pumpelly Pillar, about 1650 feet. On Pumpelly Pillar and Sinopah Mountain, white and pink quartzites are found from top to bottom of the formation, though there is a middle member in which quartzites are thin while argillites are thickly bedded and have large, flat, mud-crack polygons.

West of the Continental Divide and south of Logan Pass, the Grinnell thickens and becomes purplish red, with many thick green ledges. Near Lake Ellen Wilson, there are 3400 feet or more of red and green quartzites with interbedded white quartzites and thin beds of sandy argillite. Grinnell strata at Belton resemble siliceous green ledges of the Appekunny near Two Medicine Lake. Near Ravalli, there are no brick-red and rose tints, which are characteristic of the formation along the Lewis front.

In the Livingston Range, both green and purple diminish northward. In the vicinity of Bowman Lake, the entire Grinnell formation consists of massive red and white quartzites and minor strata of red, sandy argillite.

[45] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 674-675.

Rising Wolf Member.

DEFINITION: A basal member, in which variable white and pink quartzites are interbedded with red argillites which range from laminae to strata 5 feet thick. Symmetrical and asymmetrical ripple marks are common; mud cracks are prevalent, as are cross-bedding, mud breccias, and mud balls. Thickness, 200 to 700 feet.

TYPE LOCALITY: Southern slopes of Rising Wolf Mountain, Glacier National Park.

DISCUSSION: This member is clearly distinguished only in the eastern, dominantly argillaceous development of the Grinnell. In the Two Medicine and the Dry Fork valleys, it is dominantly a series of alternating quartzites and argillites, both of which include mud breccias. Quartzites are white to pink; argillites are deep brick red.

From Many Glaciers northward, the argillites become rose red, although quartzites are dominantly brownish gray or greenish. Green is especially conspicuous near Ptarmigan Lake; it diminishes northward and is incidental in the Blackiston section. Near Bowman Lake, the member cannot be distinguished. In the vicinity of Gunsight Mountain, quartzites are white, red, or purplish, and the argillites are purplish, red, or green, sandy and heavily bedded. Thickness, approximately 700 feet.

Red Gap Member.

DEFINITION: Argillites in thin minor and thick major beds; dominantly red, but incidentally brownish or green; interbedded with pink, white, or greenish-white quartzites, brown sandstones, and sandy argillites. Typically developed in the Lewis Range, north of Many Glaciers; recognizable elsewhere by its thick beds of red argillite with flat mud-crack polygons. Maximum thickness, 2800 feet.

TYPE LOCALITY: Mountain between Red Gap and Ptarmigan Wall, Glacier National Park.

DISCUSSION: At the type locality, this member consists of fine-grained, brick-red to rose-red argillites in thin to thick beds. Thin layers and irregular areas, 1 to 60 inches in diameter, are bluish green, apparently because hematite was reduced during metamorphism. Ripple marks and rain prints are few; mud cracks are abundant and enclose flat or slightly convex polygons. The member intergrades with transitional, quartzitic members both above and below it.

The Red Gap thins to 700 or 800 feet in Blackiston Valley, where it remains argillaceous. In the Livingston Range, south of the International Boundary, it is a medial member in which quartzites are interbedded with thick, sandy argillites whose mud cracks enclose flat polygons. Still farther southward, argillites are replaced by thin to massive argillaceous quartzites.

In the Lewis Range, the Red Gap thins southeastward until, on Pumpelly Pillar, it contains 650 feet of white or pinkish, ripple-marked, and pebbly quartzites intercalated with dark-red argillites in major beds, 10 to 40 inches thick. The strata bear fine current ripple marks, fine to coarse mud cracks, and flat polygons. Southwestward, the member thickens into 2800 feet or more of purplish and green micaceous and sandy argillites and argillaceous quartzites, with minor white interbeds in the region of Sperry Glacier and Gunsight Pass. This phase is transitional to the Grinnell of the Ravalli region south of Flathead Lake.

Rising Bull Member.

DEFINITION: Argillites, quartzites, and mud breccias forming the initial transition between the Grinnell and Siyeh; physical characteristics like those of the Rising Wolf. Thickness, 600 to 1100 feet.

TYPE LOCALITY: Upper cliffs of Mt. Rockwell (Rising Bull of the Blackfeet), south of Upper Two Medicine Lake, Glacier National Park.

DISCUSSION: Variation in this member has been described. It includes Nos. 2, 3, and 5 of Daly's Grinnell section, and Nos. 3 and 5 of that in Blackiston Valley. At Ptarmigan Wall, it is sharply separated from the pelitic Red Gap; southward, they intergrade. The southern phase is best shown in the ridge forming Cut Bank Pass, in which the basal beds are hidden. A section is as follows:

	Feet
3. Quartzite, mainly greenish, with gray, pink, and white strata; major beds 6 feet in thickness; interbedded with greenish and, in the upper parts, reddish argillite. Quartzites are strongly ripple-marked; cross-bedding is prevalent, but does not show on weathered surfaces	160
2. Argillite, dark-red, in beds 1 to 3 feet thick, interbedded with white, gray, or pink quartzite beds, 2 to 5 feet thick. The argillite shows slaty cleavage. Quartzite increases upward; in the lower and middle portions, it is cracked and rippled, contains mud breccias, and (in some beds) abundant balls of red argillite	60
1. Quartzite, white, gray, green, and red; cross-bedded; beds as much as 2 feet in thickness; interbedded with red argillites, 24 to 34 inches thick. The quartzites contain mud balls, breccias, and ripple marks, those of the uppermost bed being about 3 feet in wave length. The darker beds of quartzite are banded, generally white and red. Thin layers of argillite contain ripple marks, mud cracks, and mud breccias; thick ones generally show oblique, slaty cleavage and thin bands of green parallel to the bedding planes, yet seemingly the result of reduction. Thickness, to talus	175
	395

On Pumpelly Pillar, near Two Medicine Lake, the thickness is 600 feet, indicating 205 feet of strata beneath the Dry Fork section. Similar thicknesses are exposed on Rising Wolf and Mount Rockwell. On Going-to-the-Sun Mountain, the Rising Bull includes 700 feet of alternating red argillites and white quartzites, with minor pink beds. On the southern shoulder of Mt. Wilbur, in the Swiftcurrent region, the thickness is 900 feet; on Ptarmigan Wall it is almost 1100 feet, the quartzites and intercalated argillites and mud breccias uniting into ledges, 2 to 5 feet thick. Ripple marks are abundant and coarse; mud cracks are coarse and enclose small convex polygons bearing rain and hail prints. The upper 100 feet includes greenish sandy and micaceous argillites. Excellent sections are afforded along the trail from Ptarmigan Wall into the Belly River valley.

Southwestward, on Gunsight Pass, the Rising Wolf is 850 feet thick, unless it includes part of the quartzitic beds referred to the Red Gap. Mud cracks are abundant and coarse; they enclose small to large polygons, generally convex, in beds marked by ripples, rain, and hail prints.

PIEGAN GROUP (NOV.)

DEFINITION: Limestones, dolomites, and dominantly argillaceous clastics which lie between the Missoula and Ravalli groups. Despite variation, they form the sole dominantly calcareo-magnesian group in the Meagher facies and the second in the Glacier Park. Even in western facies, clastic strata contain much dolomite and lime. The group is characterized by great development of calcareous algae. Thickness, 2780 to 14,300 feet.

TYPE LOCALITY: Piegan Mountain, Glacier National Park. Well exposed on Mounts Gould, Wilbur, Cleveland, Lineham, and other high peaks of the Glacier-Waterton region.

DISCUSSION: Designated the "Siyeh or Wallace group" by Clapp,[46] these strata seem to require another designation. Though Willis' Siyeh possessed a greater stratigraphic range (Fig. 2, section 8), its definition specifies the dolomites and limestones below the Spokane. The Wallace of Calkins[47] may range beyond the Siyeh, but Calkins uses it as a Siyeh-Newland equivalent and apparently correlates the overlying Striped Peak with the Spokane, or with a portion of it (Fig. 2, sections 1-2). A new group name seems essential, with a type locality in which formations of the group are clearly visible. These requirements are met by the name Piegan and by Piegan Mountain itself, which shows most of the Siyeh, the Spokane, and much of the Sheppard.

In the Meagher facies, the basal Piegan consists of dark-gray or blue-gray limestones, calcareous shales, and impure, fissile limestones of the Newland formation. There are minor layers and nodules of dolomite; on the eastern slope of the Belt Mountains, the thinly bedded limestones contain abundant deformation and segregation structures called *Greysonia, Copperia,* and *Weedia* by Walcott, as well as biostromes of *Newlandia* and *Camasia.* Both limestones and shales contain the brachiopod *Lingulella montana* Fenton and Fenton.

Above the Newland lie the finely laminated olive- to brown-weathering Greyson shales, containing near the base a lenticular, pink, conglomeratic quartzite, which is best exposed on Wall Rock Butte, above 8 miles west of White Sulphur Springs. The thickness of the Greyson in the valley of Smith River was estimated at 3000 to 3200 feet; on Prickly Pear Creek, Clapp and Deiss measured 2300 feet, with the base hidden.

On Belt Creek, the Spokane shales are resistant; in the Newland Creek section, they are soft and fissile, forming rounded, rose-red hills. Thicknesses approximate the 4500 feet found on Prickly Pear Creek by Clapp and Deiss. The 600 feet of Empire "shales" exposed near Marysville completes the Spokane sequence.

In Blackfoot Canyon,[48] the dark-gray magnesian limestones of the Siyeh are 4600 feet thick; the Greyson and Empire members of the Spokane are absent. The "upper Siyeh" (Helena) reaches its maximum thickness, 6100 feet.

The Glacier Park facies is described in detail under its formations and members. It is characterized by absence of the Greyson, by marked thinning of the Spokane, by increase of clastic sediments in the uppermost formation, and by extensive limestones built directly by algae, as well as by algae in scattered colonies.

From the Little Belt Mountains to the Flathead Trench, the Wallace group is united by lower (Newland = Siyeh) and upper (Helena = Sheppard = Gateway) limestones and dolomites. In the Galton facies,[49] the Gateway contains argillites and quartzites; in the Purcell,[50] it includes these as well as conglomerates, grits, siliceous limestones, and dolomites. The lower formation also becomes dominantly

[46] C. H. Clapp: *Geology of a portion of the Rocky Mountains of northwestern Montana,* Mont. Bur. Mines Geol., Mem. 4 (1932) p. 22.

[47] F. C. Calkins *in* W. H. Emmons and F. C. Calkins: *Geology and ore deposits of the Philipsburg quadrangle, Montana,* U. S. Geol. Surv., Prof. Pap. 78 (1913) p. 35.

[48] C. H. Clapp and C. F. Deiss: *Correlation of Montana Algonkian formations,* Geol. Soc. Am., Bull., vol. 42 (1931) fig. 3.

[49] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel,* Geol. Surv. Canada, Mem. 38 (1912?) p. 161.

[50] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia,* Geol. Surv. Canada, Mem. 76 (1915) p. 34-36.

clastic, with 2000 feet of argillites, sandstones, and conglomerates. Dividing Schofield's section to conform with members and formations of the Glacier Park facies, the following section was obtained:

	Feet
GATEWAY FORMATION	
Conglomerates, argillites, grits, siliceous dolomites, and limestones	1000
SPOKANE FORMATION	
Argillites, purple and green, interbedded with sandy quarzites and porphyritic-amygdaloidal basalts (Purcell)	920+
Argillites, purple and green; may include equivalents of the uppermost Siyeh in the Glacier Park and Galton facies	500+
SIYEH FORMATION	
Limestone, thin-bedded to massive, siliceous, "concretionary," gray; weathers gray or buff	1000
Argillites and sandstones, thin-bedded, green to purple; also a lenticular conglomerate, 200 feet thick. Mud cracks abundant	2000
	5420+

Daly's Kitchener in the Moyie Range near Kingsgate was found by Schofield[51] to be another formation—the Aldridge—underlying the Creston. The Kitchener, therefore, is limited to the "western phase"—quartzites and calcareous quartzites, including (on the West Fork of Yahk River and in the McGillivray Range) typical "molar tooth." How much of these may be referred to the Siyeh is uncertain; Daly[52] correlates them with the lower 125 feet of the Gateway, the Siyeh, and (presumably) with part of the Wigwam in the Galton facies. Schofield,[53] re-defining the Kitchener, correlates it with the Wallace (= Siyeh), and the Siyeh of the Purcell facies with the Striped Peak of the Coeur d'Alene Mountains.

Clapp and Deiss[54] correlate the Kitchener and the Siyeh of Schofield's Purcell section with formations here placed in the Piegan group. This would give the group a thickness of 8500 feet, exclusive of the Gateway, which is equivalent to Clapp and Deiss' "Upper Siyeh"; it also would substitute a thick basal member of coarse clastic beds for the Collenia symmetrica zone, which is recognizable throughout the Glacier Park and Galton facies. Because of its position, lithology, and thickness, the present writers correlate the Kitchener with the Ravalli group and limit Schofield's Siyeh to equivalence with the Siyeh and Spokane formations.

SIYEH FORMATION

DEFINITION: The second dominantly calcareo-magnesian formation in the Glacier Park facies. It includes argillites, quartzites, and extensive mud breccias, as well as thick algal deposits. Dominantly, it is dark gray to black; all dolomites weather buff or fawn. Their color of weathering is not mentioned in sections. Thickness, 2900 to 4000 feet in the Lewis Range; 5400 feet in the Blackfoot Canyon facies.

TYPE LOCALITY: Mt. Siyeh, Glacier National Park.

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[51] *Op. cit.*, p. 24.

[52] R. A. Daly: *op. cit.*, Table 8.

[53] S. J. Schofield: *The pre-Cambrian (Beltian) rocks of southeastern British Columbia and their correlation*, Geol. Surv. Canada, Mus. Bull. 2 (1914) p. 12.

[54] C. H. Clapp and C. F. Deiss: *op cit.*, fig. 3.

DISCUSSION: At head of Starvation Creek, British Columbia, Daly[86] secured the section of which the following is an interpretation:

	Feet
SPOKANE AND GRANITE PARK, undivided	
Argillite, medium- to thin-bedded, reddish, with subordinate beds of gray magnesian argillites; mud cracks, rain prints, and ripple marks abundant	150
Argillites, thin-bedded, gray, and greenish, often calcareo-magnesian; mud cracks, rain prints, and ripple marks common	950
COLLENIA FREQUENS ZONE (?)	
Limestone, gray, concretionary, siliceous, with a 5-foot band of dolomite, 30 feet below the top. ("Concretions" probably are *Collenia frequens* Walcott)	100
GOATHAUNT MEMBER	
Limestone, massive, impure, magnesian, dark-gray or bluish-gray; weathers buff; interbedded with thin strata of dolomite and buff-weathering argillite, and a few thin beds of gray sandstone. "Molar tooth" structure characterizes the limestone; argillites have mud cracks and rare, obscure ripple marks	2000
COLLENIA SYMMETRICA ZONE	
Argillites and quartzites, thick- to thin-bedded, calcareo-magnesian, light- to dark-gray and greenish, with a few beds of gray dolomite without "molar tooth" structure	900
	4100

On Mt. Alderson, east of the Continental Divide, the Siyeh is 3500 feet thick; the uppermost portion, grading from dolomite into green argillite, is well exposed along the trail from Alderson to Carthew lakes. Along the Continental Divide, between Ahern and Logan passes, Glacier National Park, thicknesses of members vary considerably, this section presenting an average:

	Feet
GRANITE PARK MEMBER	
Limestones, dolomites, and dolomitic argillites interbedded with thin oölites, quartzites, and limy sandstones. Prevailingly gray to greenish. Many layers (biostromes) of *Collenia willisii* n. sp.	280– 295
COLLENIA FREQUENS ZONE	
Limestone, massive, dark-gray, crystalline, with little dolomite or siliceous material. Crowded, except in thin-bedded lenticles, with *Collenia frequens* Walcott	85– 100
GOATHAUNT MEMBER	
Magnesian limestones and dolomites, massive and thick-bedded. Near the middle, thin-bedded, greenish argillites are 200 to 300 feet thick. "Molar tooth" and mud cracks common	2000–2400
COLLENIA SYMMETRICA ZONE	
Argillites, quartzites, and sandy to argillaceous dolomites containing *Collenia symmetrica* Fenton and Fenton	550
	2915–3345

[86] R. A. Daly: *op. cit.*, p. 72.

In the Galton and Purcell facies, the Siyeh, as described by Daly[86] and Schofield,[87] consists largely of argillites and sandstones or quartzites, dolomites and limestones being thin. They are further reduced in the Coeur d'Alene facies but thicken eastward to their maximum of 5400 feet[88] on McCabe Creek (Blackfoot Canyon facies), thinning again to an estimated 2200 feet in the Meagher facies, in which, as the Newland formation, they are less dolomitic than elsewhere.

Collenia symmetrica Zone.

DEFINITION: Upper phase of the transition between the argillitic and arenaceous Grinnell to the dolomitic and limy Siyeh. Quartzites, argillites, and argillaceous dolomites weather to green, brownish, or buff; purplish-red argillites are subordinate and are limited to the lower 75 feet. Grades into the member above. Thickness, 500 to 900 feet.

TYPE LOCALITY: Ridge forming Cut Bank Pass, between the Cut Bank and the Dry Fork valleys, Glacier National Park. Well exposed on Dawson Pass and in cliffs near Grinnell Glacier.

DISCUSSION: This transition zone is distinguished by its colors, sandy dolomites, and brown quartzites. *Collenia symmetrica* Fenton and Fenton is found throughout and is a reliable horizon marker. The section at the type locality is as follows:

	Feet
9. Dolomite, argillaceous, dark-gray; beds 8 to 12 inches thick, layers thin and uneven. Several beds contain widely expanded algae unlike those of No. 8, but referable to *Collenia symmetrica* Fenton and Fenton	140±
8. Dolomite, dark-gray to black, in one massive bed. Crowded by *C. symmetrica* Fenton and Fenton	2
7. Limestone, dark-gray, in beds 2 to 6 inches thick	17
6. Argillite, blue-green, finely laminated; iron-stained basally. Interbedded with bluish to brownish ripple-marked quartzite in strata 2 to 4 inches thick, and thicker beds of greenish, argillaceous limestone containing mud cracks	154
5. Dolomite, green-gray. Upper surface irregular and deeply channeled	2-3
4. Quartzite, white, in beds 12 to 20 inches thick; weathers brownish; interbedded with blue-green and dark-red argillites showing slaty cleavage, and some greenish, mud-cracked, argillaceous limestone	102
3. Quartzite, white to greenish, in beds 4 to 12 inches thick; ripple-marked. Interbedded with buff-green shale	10
2. Dolomite, light-gray; contains large, hemispheroidal colonies of *C. symmetrica* Fenton and Fenton	3
1. Dolomite, gray; includes mud breccias. Interbedded with blue-green to red, limy argillites and green to buff quartzite. Colonies of *C. symmetrica* Fenton and Fenton are small	38
	469±

Annelid burrows occur in quartzites, probably of No. 1, on Dawson Pass, and in higher strata (No. 4?) near Sexton Glacier, above the St. Mary Valley.

Near Many Glaciers, this member is about 500 feet thick and contains much blue-green argillite. It thickens to 700 feet below Indian Pass, containing imperfect "molar tooth" in some beds. Near Alderson Lake, Waterton Lakes Park, the

[86] *Op. cit.*, p. 104-105.

[87] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) p. 33-35.

[88] C. H. Clapp and C. F. Deiss: *op. cit.*, fig. 3.

Collenia symmetrica zone includes 800 feet of argillaceous and sandy beds, which weather fawn rather than greenish or gray buff. Daly's Siyeh Starvation Creek section[59] shows 900 feet of similar beds.

Goathaunt Member.

DEFINITION: Limestones, dolomites, and subordinate oölites, dolomitic sandstones, and argillites, thickly bedded; prevailingly dark-gray. Mud breccias, commonly containing coarse sand and pebbles, are abundant in northern exposures. Mud cracks are common in carbonaceous layers; ripple marks are obscure. *Collenia willisii* n. sp. common, especially in the Lewis Range. Thickness, 2000 to 3200 feet.

TYPE LOCALITY: South wall of the cirque between Mt. Goathaunt and Mt. Cleveland. Well exposed in high peaks of Waterton-Glacier parks.

DISCUSSION: Near Piegan and Swiftcurrent passes, the Goathaunt consists of massively bedded, dark-gray to black, magnesian limestone with minor beds of oölite, edgewise breccia, and argillaceous limestone. "Molar tooth" structures abound; mud cracks are abundant; ripple marks are uncommon. Whitish metamorphosed zones adjoin sills and dikes. Algae are uncommon in the Goathaunt near Swiftcurrent Pass, but on Going-to-the-Sun and Cataract mountains, colonies of *Collenia willisii* n. sp., 3 to 5 feet in diameter and interbedded with oölites, mud-cracked beds, and edgewise breccias, are abundant throughout the upper half of the member.

In Iceberg Lake cirque the minor green argillites of southern exposures thicken and include flat-pebble breccias. Northward, thin red beds are found among the green. At Indian Pass, *Collenia* occurs throughout the Goathaunt member; strata are mud cracked and earthy. The upper half of the member contains many beds composed of thin, shattered layers; they weather to ledges resembling the Sheppard formation on Boulder Pass. Resistant beds are formed chiefly by hard, black algae.

On the north face of Mt. Cleveland, the "limestones" are resistant, with many beds of green and red argillite. These are thinner in the Boulder Pass region, where the Goathaunt is massively bedded and forms steep cliffs. The estimated thickness is 3200 feet or more.

In the Livingston Range of Canada, the Goathaunt member thins, being 2000 feet at the head of Starvation Creek. On Mt. Alderson, it consists of massive, dark-gray dolomite. Mud breccias contain quartz and chert pebbles (Pl. 2, fig. 1). In the Galton facies, the Goathaunt consists of 2000 feet of siliceous dolomite and limestone, interbedded with red and green argillite.[60]

Collenia frequens Zone.

DEFINITION: Dark-gray, crystalline to amorphous limestones in one or more massive biostromes with thinly bedded calcareous or dolomitic intercalations. Biostromes consist of little except *Collenia frequens* Walcott and *C. versiformis* n. sp. Thickness, 100 to 156 feet.

TYPE LOCALITY: Eastern slope of Swiftcurrent Pass on the Granite Park trail. Illustrated by Campbell[61] and the writers.[62]

DISCUSSION: Massive, gray-weathering ledges of this zone are exposed on almost every high peak in Waterton-Glacier parks. Thicknesses vary, the greatest (156

[59] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 72.

[60] *Op. cit.*, p. 104.

[61] M. R. Campbell: *The Glacier National Park: a popular guide to its geology and scenery*, U. S. Geol. Surv., Bull. 600 (1914) pl. 5 B.

[62] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) pl. 9.

feet) being measured below Swiftcurrent Pass, Glacier National Park. In Daly's Starvation Canyon section, this zone appears as 100 feet of "concretionary, silicious and non-magnesian limestone weathering light gray, with a five-foot band of buff-weathering dolomite at thirty feet from the top." In Hole-in-the-Wall Basin the section is:

	Feet
7. Limestone, blue-gray, shaly, without conglomerate; bedding thin	12–13
6. Limestone, gray, irregularly bedded, showing "molar-tooth" structure. Upper beds consist of coarse, flat-pebble conglomerate	7
5. Limestone, gray, massive; crowded by *Collenia versiformis* n. sp. in irregular nodules, many of which approximate small reefs	15
4. Limestone, gray, shaly, in beds 3 to 6 inches thick, with numerous partings	6
3. Limestone, like No. 2, but crowded by elongate masses 3 to 6 inches in diameter and 20 to 30 inches in height, the columnar form of *C. versiformis* n. sp.	4–10
2. Limestone, gray, massive; few bedding planes discernible. Crowded by masses of *C. frequens* Walcott	50
1. Limestone, dark blue-gray, very fine-grained, in beds 8 to 10 inches thick. Contains *C. frequens* Walcott, sparsely distributed. Much fractured, weathering into small, angular chips	4
	100±

From Swiftcurrent Pass southward, the zone consists primarily of *Collenia frequens* Walcott growing in compact masses, though the expanded ecad is common. *C. versiformis* is uncommon south of Iceberg Lake.

Granite Park Member.

DEFINITION: Magnesian limestones, oölites, argillites, and quartzites represent the final stage of Siyeh sedimentation. Colors range through gray, greenish gray, and brown; textures vary areally. Large colonies of *Collenia willisii* n. sp. are abundant at several horizons. Thickness, 280 to 900 feet.

TYPE LOCALITY: Cliffs of the Continental Divide southeastward from Granite Park, Glacier National Park, where the strata are crossed by a trail to the dike above Grinnell Glacier. Well exposed in Hole-in-the-Wall Basin, near Boulder Peak, and on the trail from Alderson to Carthew lakes, Waterton Lakes Park.

DISCUSSION: At the type locality, the Granite Park consists of 285 feet of dolomites, argillites and thin quartzites, with thin strata of oölite, sandstone and mud breccia. *Collenia willisii* n. sp. is found at several levels, in flattened colonies, 1 to 4 feet in transverse diameter. Alternations of sediments are numerous, involving many lenses.

Northwestward, on the crest of the Lewis Range, the member preserves its general character, though clastic materials diminish, and algae become pinkish gray. In the Livingston Range, near Brown Pass, there are few argillites or sandstones, as the following section, continuous with that of the Collenia frequens zone, shows:

	Feet
14. Limestone, gray, fine-grained; crowded with masses of *Collenia* similar to those of No. 11, but smaller	3
13. Limestone, blue-gray, weathers buff, in beds 2 to 3 feet thick; some beds of gray shaly limestone. *C. willisii* n. sp. much smaller than in No. 11; few in number and scattered	17±
12. Limestone, gray, weathers dark buff gray; virtually filled by colonies of *C. willisii* n. sp. 6 to 12 inches in diameter and 2 to 48 inches thick	12±

	Feet
11. Limestone, buff to gray, in beds 2 inches to 3 feet in thickness. Algae at several levels; large but not abundant. Largely talus-covered	82
10. Limestone, gray, massive, thickly bedded; contains relatively thin, widely expanded masses of *Collenia*	5
9. Limestone, gray to gray-buff; major bedding heavy, minor bedding thin; all bedding uneven. Some beds are noduliferous; others show "molar-tooth" structure. *C. willisii* n. sp. closely crowded in several layers	75
8. Limestone, blue-gray, with much clastic material. Contains abundant, broadly expanded colonies of *C. willisii* n. sp.	2–3
	197±

The Granite Park member contains many algal reefs or bioherms, of which two have been described.[63] Exposed on the Going-to-the-Sun Highway, 6.4 miles westward from Logan Pass and 1.4 miles above the "big switchback," they are more available than small bioherms near the trail north of Flattop Mountain, and are better exposed than others near the highway tunnels. All show depression and squeezing of subjacent beds, but off-reef strata indicate little sliding.

Recent exposure of the upper part of the large biostrome on the highway necessitates a new section (Plate 17). A basal, partly diagenized core, extending almost to the Collenia frequens zone, consists of that species in its conical form. A second, smaller core contains conical and crumpled-laminar colonies of *Collenia frequens* Walcott. An indistinctly stratified member, continuous with the off-reef, overlies it and contains a few irregular algae, doubtfully referable to *C. frequens*. Above this is a third, large biostrome, in which colonies of *C. frequens* are rare, but the columnar colonies of *C. versiformis* n. sp. are abundant. They grade into, or lie among, much larger colonies, some of which seem to be *C. versiformis*, though others are *C. willisii* n. sp.[64]

SPOKANE FORMATION

DEFINITION: Argillaceous and arenaceous strata lying between the calcareo-magnesian formations of the Piegan group. The beds range from sandstones and soft shales to quartzites and argillites; dominantly red and green, though brown, buff, and gray are also seen. Thickness, 180 to 7400 feet.

TYPE LOCALITY: Spokane Hills, east of Helena, Montana.

DISCUSSION: Argillites, interbedded with green basalts, lie above the Siyeh formation, from Dawson Pass northward through Waterton Lakes Park and in the Purcell Range. At Hole-in-the-Wall Basin, 2.2 miles south of the 49th parallel, they afford the following section:[65]

	Feet
10. Argillite, light-greenish to brown, interbedded with brown to greenish quartzites 4 to 20 inches thick	14
9. Argillite, light-greenish to buff, interbedded with buff argillaceous limestone	6
8. Diabase, dark-greenish, more massive than No. 6; flow structures pronounced; pipes, pillows, and inclusions of sediment abundant, the latter only basally	180–200

[63] C. L. Fenton and M. A. Fenton: *Algal reefs or bioherms in the Belt series of Montana*, Geol. Soc. Am., Bull., vol. 44 (1933) p. 1135-1142.

[64] *Op. cit.*, p. 1141. Referred originally to *C. frequens*.

[65] Hole-in-the-Wall member of C. L. Fenton and M. A. Fenton. [*Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 673. This name is a synonym of Spokane.]

	Feet
7. Argillite, green, finely banded; hard and much fractured. Upper part commonly included in the superjacent diabase	3– 5
6. Diabase, dark-greenish; pillows and flow structures less pronounced than in No. 8. Thickness increases eastward from Boulder Glacier	6– 20
5. Argillite, dark-green, finely banded, with several sandy layers. Ripple marks large, but present only in upper layers. Near the top is a metamorphosed red layer 6 to 8 inches thick; near the bottom, a bed containing altered colonies of *Collenia undosa* Walcott	16
4. Argillite, with several beds of quartzite, both dark and red, and some layers of brownish-red conglomerate. Cross-bedding, ripple marks, and mud cracks throughout	75
3. Argillite, red, buff, and buff-red in lower portions, grading upward into greenish, and terminating in red argillites interbedded with quartzite. Ripple marks, mud cracks, and cross-bedding common in the quartzites	270
2. Argillite, greenish to buff; major beds 2 to 3 feet thick; minor beds are thin	15
1. Magnesian limestone, gray to buff, thinly bedded, shaly; grades upward into argillite, yellow to reddish and finely mud-cracked	60
Sediments	470±

At Swiftcurrent Pass the lavas are 30 to 60 feet thick; they terminate about 0.8 mile south of the pass. The argillites are 180 feet thick near the western switchback on the Going-to-the-Sun Highway. They are exposed along the Divide, from Pollock Mountain to the region of Logan Pass, where their thickness on Clements, Reynolds, and other mountains is about 700 feet. South of Glacier Park, in the valley of the Middle Fork of the Flathead, their thickness is estimated at 800 feet. Mud cracks and symmetrical ripple marks are abundant.

Western facies of the Spokane are discussed in connection with the Piegan group. Southward, in both the Blackfoot Canyon and Meagher facies, the Spokane thickens and ranges from soft, friable, red and green shales to massive argillites and sandstones. In the typical Meagher facies, it contains:

	Feet
EMPIRE MEMBER	
Argillites, thickly bedded, siliceous, greenish-gray, with some sandstones and limestones. Two "Cryptozoan" *(Collenia?)* beds reported by Walcott.[66]	600±
PRICKLY PEAR MEMBER (nov.)	
Argillites interbedded with sandstones and lenticular conglomerates. Mud cracks and ripple marks common	3000–4500
GREYSON MEMBER	
Shales, thinly bedded, gray, and greenish gray; weather olive-brown. Conglomerates, pinkish sandstones, and brown sandy lenses in lower portion; upper parts thinly bedded and fissile	2300–3000+
Actual thicknesses	5100–7400+

In the Little Belt Mountains, the Spokane becomes rose red, fissile shale, and the Greyson is reduced to approximately 1000 feet of gray argillite. Sections supposedly containing fossils were not examined.

[66] C. D. Walcott: *Algonkian formations of northwestern Montana*, Geol. Soc. Am., Bull., vol. 17 (1906) p. 10.

SHEPPARD FORMATION

DEFINITION: Argillaceous and siliceous dolomites and magnesian limestones in thin strata but thick beds; dark-gray, green-gray, or brown. Basally, there are interbeds of greenish-white magnesian quartzites. Ripple marks, mud cracks, channel fillings, and edgewise mud breccias are characteristic, the latter chiefly in siliceous layers; there is little or no red argillite. This formation represents the final stage of Piegan calcareo-magnesian sedimentation. Thickness, 585 to 1500 feet.

TYPE LOCALITY: Cliffs of the Lewis Range near Sheppard Glacier. Well exposed on Mt. Carthew, Boulder, and Swiftcurrent peaks, and mountains near Logan Pass, as well as in the valley of the Middle Fork of the Flathead River.

DISCUSSION: Willis[67] characterizes this formation as "quartzite, yellow, ferruginous," lying above the Purcell and below the red, argillaceous Kintla. Quartzites are dominant, however, only in 20 to 50 feet of green and pink strata which overlie the Purcell lava, but are continuous with the Spokane. Above them is a brown to gray dolomitic formation with minor sandstones and quartzites in its basal portion. At the head of Starvation Canyon, British Columbia, Daly[68] records:

	Feet
3. Dolomite, siliceous, thin-bedded, weathers buff	500
2. Lava, basic, amygdaloidal	35
1. Sandstones and interbedded argillites, medium- to thin-bedded, reddish and gray, with thin, buff-weathering, dolomitic beds	50
	585

Of these, No. 1 is assigned to the Spokane; No. 2 is a Purcell eruption that did not reach Glacier National Park; No. 3 is typical Sheppard, 570 to 590 feet thick near Boulder Pass, where a 40-foot basal zone contains quartzites. Edgewise breccias (Pl. 3, fig. 2) interbedded with porous, sandy beds containing abundant channel fillings (Pl. 3, fig. 1) are found in the uppermost 150 feet.

The Sheppard thickens southward; in Glacier National Park, it contains much brown-weathering rock in which dolomite layers are cracked, crumpled and intercalated with dark-gray limestone (Pl. 8, fig. 1). Best exposed near Granite Park, it also forms thick, firm beds along the Middle Fork of the Flathead River and on the Belton Hills. These massive beds resemble the dark-gray Siyeh rather than the crumbly strata at Boulder Pass. Estimated thickness, 1500 feet.

In the MacDonald and Galton ranges of British Columbia, Daly[69] describes 2025 feet of Gateway (= Sheppard) strata, which the writers group into two members, as follows:

	Feet
2. Argillite, siliceous, thin-bedded, light-gray to greenish-gray; weathers gray, brownish gray, red, or reddish brown. Interbedded with quartzitic sandstone. Ripple marks, rill marks, mud cracks, and casts of salt crystals, 0.5 to 2 centimeters thick, are common. Estimated thickness	1850
1. Sandstone, coarse to fine, gray, interbedded with dolomite and ferruginous limestone. Some lenses of fine conglomerate	125
	1975

[67] Bailey Willis: *Stratigraphy and structure, Lewis and Livingston ranges, Montana*, Geol. Soc. Am., Bull., vol. 13 (1902) p. 316.

[68] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 78.

[69] *Op. cit.*, p. 107-108.

Beds of buff- to brown-weathering dolomite lie 50 feet above the base of the sandstone. They contain "concretions," apparently *Collenia*, which Daly describes as "spheroids or ellipsoids composed of dolomite in concentric layers separated by thin laminae of cherty silica. The diameter of the bodies varies from a few inches to a foot or more." They are much larger than algae in the lower Sheppard of Boulder Pass.

Schofield[70] describes the Gateway (= Sheppard), in the McGillivray Range, as fine-grained grit containing pebbles of Purcell lava and quartzite, overlain by alternating beds of conglomerate and siliceous limestone, with some dolomites and interbedded purple shales and gray sandstones. Above these are sandy argillites with casts of salt crystals, and heavily bedded sandstones and quartzites, the total thickness being approximately 2025 feet.

The Sheppard may be represented in the Coeur d'Alene facies by the Striped Peak,[71] described as siliceous, shaly limestones, chiefly green and purple, containing ripple marks and mud cracks, and measuring 1000 feet in thickness. Probably, however, the Sheppard is absent (Fig. 2, section 1).

Southward from Glacier National Park, the Sheppard is termed Blackfoot, Helena, and "Upper Siyeh." Walcott[72] defines the Helena as thickly bedded, impure, bluish-gray, and gray limestone, interbedded with irregular oölites, concretionary limestones, bands of dark-gray siliceous shale, and greenish to purplish argillaceous shale. The thickness is 4000 feet in Prickly Pear Canyon and 6100 in Blackfoot Canyon,[73] where Walcott applies the name Blackfoot.[74]

MISSOULA GROUP

DEFINITION: Argillites, quartzites, and sandstones, with minor beds of conglomerate, limestone, and calcareous shale.[75] Ripple marks, mud cracks, salt crystal casts, and rain prints are characteristic. Thickness, 10,000 to 18,000 feet.

TYPE LOCALITY: Slopes east and west of Rattlesnake Creek, northeast of Missoula, Montana.

DISCUSSION: The term Missoula antedates and reduces to synonymy the writers' "Boulder Pass Formation",[76] based on the outcrop of Missoula strata which extends westward and northward from Kootenai Peak, above Waterton Valley. Its highest member appears on Mt. Rowe, north of Akamina Pass. Another outcrop lies between the Middle Fork of the Flathead River and the Flathead Range, from Nimrod to the mouth of Coal Creek. Here, the stream follows a branch of the Roosevelt Fault;[77] along the right bank, Grinnell and Siyeh strata dip eastward, while on the left, Missoula strata dip at angles of 40 to 52 degrees, and strike N18°-24°W. An estimated thickness of 7500 feet is verified by Clapp and Deiss'

[70] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) p. 36-37.

[71] F. C. Calkins and F. L. Ransome: *Geology and ore deposits of the Coeur d'Alene district, Idaho*, U. S. Geol. Surv., Prof. Pap. 62 (1908) p. 25, 27, 44.

[72] C. D. Walcott: *Pre-Cambrian fossiliferous formations*, Geol. Soc. Am., Bull., vol. 10 (1899) p. 207.

[73] C. H. Clapp and C. F. Deiss: *Correlation of Montana Algonkian formations*, Geol. Soc. Am., Bull., vol. 42 (1931) fig. 3.

[74] C. D. Walcott: *Algonkian formations of northwestern Montana*, Geol. Soc. Am., Bull., vol. 17 (1906) p. 5-7.

[75] C. H. Clapp and C. F. Deiss: *op. cit.*, p. 677-695.

[76] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 672.

[77] C. H. Clapp: *Geology of a portion of the Rocky Mountains of northwestern Montana*, Mont. Bur. Mines Geol., Mem. 4 (1932) pl. 1.

figure of 7600 feet. The basal (Miller Peak) formation of the Missoula can be recognized, with a thickness of about 2800 feet; above it are alternating argillites and quartzites, dominantly green and red, which are grouped as Missoula, undifferentiated.

MILLER PEAK FORMATION

DEFINITION: Argillites, thinly bedded, dominantly green and red but with a buff-weathering member. Interbedded argillaceous quartzites and sandstones and two lenticular biostromes of limestone. This represents the initial stage of Missoula clastic sedimentation. Thickness, 2800 to 2900 feet.

TYPE LOCALITY: Miller Peak, southeast of Missoula, Montana.

DISCUSSION: The Miller Peak of the Glacier Park facies includes three members, which are more distinct in Waterton Lakes Park than they are near the Middle Fork of the Flathead River. Lithic resemblance suggests the correlation with Clapp and Deiss' type section,[78] which is indicated in Figure 2.

Kintla Member.

DEFINITION: Argillites and argillaceous sandstones, thinly bedded, dominantly bright red; thin beds of quartzite and pinkish gray limestone. Contains 30 to 40 feet of purplish amygdaloidal lava. Ripple marks, mud cracks, channels, rain prints, and casts of salt crystals are characteristic; algae are present only in dolomites, which they form. Thickness, 860 to 900 feet.

TYPE LOCALITY: Pyramidal peaks of Akamina Ridge, west of Waterton Lakes National Park. Well exposed on Mt. Rowe, Mt. Carthew, Mt. Custer, and on Boulder Peak.

DISCUSSION: Willis[79] remarks that the Kintla member indicates recurrence of "extremely muddy, ferruginous" sediments comparable to the Grinnell. Daly[80] notes the presence of angular grains of quartz, fresh microcline, microperthite and cloudy orthoclase in argillaceous hematite-stained cement.

Sections of the Kintla at and near the type locality show:

	Feet
6. Argillite, thin-bedded and homogeneous, bright-red to purplish or brownish-red; minor beds of quartzite and sandstone	440–460
5. Argillite, thin-bedded, bright-red to brownish, interbedded with red, brown, or brownish-gray sandstone, the latter increasing northward	175–200
4. Limestone, gray to pinkish-gray, weathers pink. Bears two algal bioherms composed of *Collenia clappii* n. sp.	20– 30
3. Argillite, thin-bedded, bright-red, with layers of argillaceous red sandstone	95–100
2. Lava, amygdaloidal, green to purplish	40– 50
1. Argillite, thin-bedded, bright-red, with dull-red magnesian quartzites	60
	830–900

At the head of Starvation Canyon,[81] No. 1 is 10 feet thick, No. 4 is lacking, and no oölites were found in overlying magnesian beds. Southward to Kootenai Peak, the basal member thickens by increase in the red quartzites, but Nos. 3 and 4 are partly removed. Kintla strata in the Flathead Range are approximately 600 feet thick. They are dull red and include much thick-bedded but thin-layered green argillite. Mud cracks are abundant and enclose large polygons; symmetrical and

[78] C. H. Clapp and C. F. Deiss: *op. cit.*, p. 678.
[79] Bailey Willis: *op. cit.*, p. 324.
[80] R. A. Daly: *op. cit.*, p. 83.
[81] *Op. cit.*, p. 82.

intereference ripple marks are common. Rain prints are numerous, though salt crystals are relatively uncommon.

Near Elko, British Columbia,[82] the Gateway (= Sheppard, Helena) formation is overlain by 500 feet of purplish and red argillites and sandstones, with thin sandy argillites. Thickness, lithology, and stratigraphic position indicate that this formation, called the Phillips by Daly,[83] is a western phase of the Kintla. In the Galton Range, Daly finds "about 550 feet of dark, purplish or brownish red, fine-grained to compact metargillite and metasandstone in alternating thin beds. At the base three massive beds of gray quartzitic sandstone, respectively four, ten, and twenty feet thick, are intercalated. Sun-cracks and ripple-marks are again plentiful. No salt crystals were found . . ." nor was any contemporaneous lava, a fact which, combined with the absence of lava along the Middle Fork of the Flathead River, indicates that the Kintla flow was narrowly localized as well as thin.

Roosville Member.

DEFINITION: Thin-bedded, fissile argillite and argillaceous sandstones, green, green-gray, and olive; weather rusty buff, light gray, or brown. Mud cracks, ripple marks, and salt crystals are common. Thickness, 550 to 1000 feet.

TYPE LOCALITY: Three miles east-northeast of the Phillips Creek cascade, near Roosville, British Columbia.

DISCUSSION: The Roosville of the Purcell facies includes 600 to 675 feet of "thin-bedded, light green, light gray, and greenish gray silicious metargillite bearing thin, . . . quarzitic, interbeds",[84] which resemble the dominant phase of the Gateway formation. On Mt. Carthew and Mt. Rowe in Waterton Lakes Park, the Roosville contains about 550 feet of thinly bedded, buff to olive-green, siliceous argillites which show ripple marks and casts of salt crystals. In the Middle Fork section, Roosville argillites are micaceous, dull green, and approximately 600 feet thick.

The Roosville in Elk River Canyon, British Columbia,[85] contains 1000 feet of massive but thinly laminated, siliceous green argillites—Dawson's "Elk River Bridge beds."[86] Four miles north of Elko, the upper Roosville argillites contain unidentified algae.[87]

Mt. Rowe Member (nov.)

DEFINITION: Red quartzites, in thin to thick beds, many of which show cross-bedding, ripple marks, and mud conglomerates. The quartzites grade upward into rose-red argillites, which are thinly bedded and fissile. Thickness, about 1500 feet.

TYPE LOCALITY: South crest of Mt. Rowe, near Akamina Pass, Waterton Lakes National Park.

DISCUSSION: The Mt. Rowe member contains more quartzite and mud conglomerate than does the Kintla, and its color is rose, not bright brick-red. Salt crystals and rain prints are less abundant than in the Kintla, or in the underlying Roosville.

About 1500 feet of dominantly red argillites in the Middle Fork section are correlated with the Mt. Rowe of Waterton Lakes Park. The Mt. Rowe seems to be

[82] S. J. Schofield: *op. cit.*, p. 42.

[83] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 108-109.

[84] *Op. cit.*, p. 109, 110.

[85] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) p. 42.

[86] G. M. Dawson: *Preliminary report on the physical and geological features of that portion of the Rocky Mountains between latitudes 49° and 51° 30'*, Geol. Surv. Canada, Ann. Rept. 1, B (1886) p. 78.

[87] S. J. Schofield: letter.

represented on Miller Peak by 1440 feet of red and purplish beds and perhaps by 235 feet of superjacent purple argillitic sandstones, apparently transitional between the dominantly argillaceous Mt. Rowe and the sandy Hellgate.

UNDIFFERENTIATED MISSOULA GROUP

About 4800 feet of argillites and sandstones overlies the Miller Peak formation in the Flathead Range. Small symmetrical ripple marks and interference marks are abundant, as are mud cracks, which enclose flat polygons in argillites and convex polygons in quartzites. Polygons range from 1 to 36 inches in width. Large ones are secondarily cracked. Rain prints are numerous in some layers; others show annelid burrows.

IGNEOUS ROCKS

The Belt series in the Glacier Park facies includes igneous rocks of two types: diabasic basalt lavas in the Grinnell, Spokane, and Kintla, and gabbro or gabbro-diorite sills and dikes cutting formations from the Altyn to the Spokane. In addition, there are minor exposures of augite-andesite, melanite, phonolite, and other rocks.[88]

The earliest lava is the basic amygdaloidal basalt in the Rising Bull member of the Grinnell formation. West of the Continental Divide, it resembles the Purcell lava and, as described by Daly,[89] is composed largely of secondary chlorite, quartz, and calcite, with abundant labradorite crystals and pores filled by deep-green chlorite. Through oversight, it appears as "intrusive" in the first Belt section published by the present authors.[90] It is well exposed on Blackiston Brook, below Red Rock Canyon, Waterton Lakes Park.

The second lava is the Purcell.[91] At its most southerly exposures, west of Grinnell Mountain, the Purcell includes two major flows, the first, 30 to 42 feet in thickness, the second 18 feet thick. The basal 20 to 25 feet of the lower flow contains ellipsoids or "pillows", 10 to 25 inches in diameter, separated by cherty inclusions; the lavas surround detached masses of modified argillite 2 to 12 feet thick, the base being irregular. The upper 10 to 17 feet is a massive, ropy lava. The second main flow is massive and amygdaloidal, containing mud inclusions, steam tubes, and irregular cavities—evidences of subaqueous extrusion.[92]

Northward, the thickness and number of flows increase. There is 150 feet of lava on Mt. Kipp and 175 feet on Cathedral Mountain, 200 to 220 feet in Hole-in-the-Wall Basin, 275 feet west of Boulder Pass, and 275 to 300 feet in Waterton Lakes Park. Above Pocket Lake, on Boulder

[88] G. I. Finlay, *in* Bailey Willis: *Stratigraphy and structure, Lewis and Livingston ranges, Montana*, Geol. Soc. Am., Bull., vol. 13 (1902) p. 351-352.

[89] R. A. Daly: *op. cit.*, p. 70.

[90] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 674.

[91] R. A. Daly: *op. cit.*, p. 79, 207-220.

[92] L. D. Burling: *Ellipsoidal lavas in the Glacier National Park, Montana*, Jour. Geol., vol. 24 (1916) p. 235-237.

Peak, eight flows were counted in the upper 100 feet of lava. Daly's sections [93] show 390 feet of amygdaloid, porphyry, and mud breccia in the Galton Range and 465 feet of varied lavas in the Purcell. "Pillows," irregular inclusions, vesicles, steam tubes, and ropy structure characterize the flows. Prevailing colors are dark blue green to olive green.

A 40-foot bed of dark-green to purplish amygdaloidal basalt in the Kintla formation contains steam tubes especially well developed. Neither ropy surfaces nor "pillows" are typical.

Dikes occur in the Altyn, Appekunny, Grinnell, and Siyeh. Those of the first three are olive green, contain minor amounts of copper, and are much metamorphosed. One strikes northwestward from the Roes Creek campground to Roes Basin, Glacier National Park; it probably joins the larger dike exposed near Cracker Lake. Differences from Siyeh dikes suggest that these were associated with the Grinnell flow.

Siyeh sills, 40 to 120 feet thick, lie at various levels; they overlap on Fusilade Mountain and on the ridge between Mt. Pollock and Mt. Gould. They are reached by numerous dikes, which are conspicuous in the eastern cliffs of Mt. Gould, on the trail below Swiftcurrent Pass, and on the north face of Mt. Cleveland. Both dikes and sills consist of dark-gray to greenish, altered gabbro-diorite or abnormal gabbro.

Dikes, slightly crystalline and brownish-green, rise above sills on Allen Mountain, on the Garden Wall above Grinnell Glacier, on mountains northwest of Ahern Pass, near the head of Valentine Valley, in the cirque wall below Carthew Lakes, and near Alderson Lake. The Valentine and Alderson dikes seem to cut the Siyeh sills, but the Carthew dike joins the Purcell lava. They complete the following sequence of igneous events in the Glacier Park facies:

Early Kintla	Basaltic flow, 40 feet thick, subaqueous.
Late Spokane	Basaltic flows, 35 to 275 feet thick; subaqueous.
Early Spokane or latest Siyeh	Intrusions in sheets and dikes, the latter as much as 300 feet wide (at the foot of Lake Janet). They rose within 350 feet of the top of the Siyeh.
Late Grinnell (Rising Bull)	Basaltic flow and copper-bearing intrusions. Flow 20 to 40 feet thick; probably subaqueous.
(Localized intrusions of undetermined dates; probably Altyn in part.)	

[93] R. A. Daly: *op. cit.*, p. 219.

PART II. SEDIMENTATION

SEDIMENTARY STRUCTURES

MUD BRECCIAS

Terminology.—The Glacier Park facies of the Belt contains no interformational conglomerates, but abounds in those to which Walcott's term intraformational conglomerates [94] generally is applied, though Walcott himself separated part of them as breccias,[95] and Calkins distinguished one type as mud-breccias: "rocks containing angular or slightly rounded fragments . . . embedded in somewhat coarser-grained and more arenaceous material." [96] Hadding [97] uses mud-cake conglomerate and desiccation conglomerate for physically similar rocks. Of these several terms, Calkins' seems most effectively descriptive, though it requires re-definition and division.

A *mud breccia* is a rock containing angular or slightly rounded fragments embedded in a matrix, which generally is less compact and coarser than they. In many deposits, the matrix lacks laminae or layers. Matrix and fragments may consist of identical or of very different material, depending upon details of origin.

A *flat-pebble breccia* is a mud breccia whose pebbles are approximately horizontal. In many deposits, the narrow edges of pebbles are well rounded, though some fragments are sharply angular.

An *edgewise breccia* is a mud breccia whose fragments or pebbles lie at various angles; many of them are curved to match cross-laminae.

Conglomerate may be substituted for breccia in any of the definitions if fragments are sufficiently rounded to warrant its use. No Belt deposits demand this distinction.

Description.—Mud breccias have not been observed in the Waterton member of the Altyn formation, perhaps because of inadequate exposures. In the Hell Roaring member, strata containing gravel and sand also contain angular flat pebbles in both horizontal and oblique positions. A typical specimen from Forty-mile Creek, south of the Two Medicine Valley, is shown in Figure 1 of Plate 5; the pebbles are less dolomitic than the matrix and some are finely laminated. Similar pebbles are found in sandy beds among and above the biostromes of *Collenia columnaris* Fenton and Fenton, near Appekunny Falls.

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[94] C. D. Walcott: *Paleozoic intra-formational conglomerates*, Geol. Soc. Am., Bull., vol. 5 (1894) p. 191-198; *The Cambrian rocks of Pennsylvania*, U. S. Geol. Surv., Bull. 134 (1896) p. 34-40.

[95] C. D. Walcott: *Paleozoic intra-formational conglomerates*, Geol. Soc. Am., Bull., vol. 5 (1894) p. 192.

[96] F. C. Calkins in F. L. Ransome and F. C. Calkins: *Geology and ore deposits of the Coeur d'Alene district, Idaho*, U. S. Geol. Surv., Prof. Pap. 62 (1908) p. 31.

[97] Assar Hadding: *The pre-Quaternary sedimentary rocks of Sweden*, II, Lunds Geol.-Min. Instit., Med. no. 32 (1927) p. 60-110; *On subaqueous slides*, Geol. Fören. Stockholm, Förh. (1931) p. 384.

Blue-gray limestones and interlaminated buff-weathering dolomites, interbedded with thin biostromes of the alga *Collenia albertensis* n. sp. in a virtually unlaminated matrix, are exposed along the lake-shore trail south of Waterton Lakes Park. They contain edgewise pebbles or cakes of limestone, 3 to 52 mm. in diameter and 1.5 to 12 mm. thick; their edges are rounded. There also are subangular pebbles, 2 to 13 mm. in thickness.

The algal colonies (Fig. 15) are upright and undisturbed, indicating that the pebbles were dropped among them, not transported by slides. The development of secondary bases on some colonies indicates periodically rapid accumulation of sediment. Similar expansions mark bryozoans of Cincinnatian strata in which wave action seems to have stirred up both mud and pebbles and re-deposited them about the colonies, which then spread out on the new bottom.

Mud breccias in the Appistoki member are limited to finely laminated argillites. They range from slightly disturbed beds of mud cracks whose polygons reach widths of 105 mm., and are sharply angular, to beds from which all traces of crack pattern have disappeared. In these, the pebbles are generally less than 25 mm. in length, commonly less than 15 mm., and grade downward to minute subovate cakes or triangular chips. Small fragments fill spaces between the large ones, all lying so nearly in one plane that the thickness of a given conglomerate lamina may be only 2 to 5 mm. Good examples of these thin beds and rounded pebbles are found in talus above Appekunny Falls, though they are common throughout the Appistoki and in brown, green, and purplish argillites of the Scenic Point member. Its most characteristic breccias, however, consist of greenish or purplish pebbles, either flat or inclined at low angles in a brown sandstone matrix, which is much like the material filling mud cracks in underlying red argillites (Pl. 7, Fig. 2). Pebbles are less rounded than those of the argillite beds, as if they had been buried too quickly for effective wear. Mud breccias are abundant in quartzitic members of the Grinnell. A typical red breccia with white sand matrix is shown in Figure 3 of Plate 5. Pebbles are oval to subangular, flat or warped; several are concavo-convex, with the essential characters of mud-crack polygons. Pebbles intermingled with mud balls in cross-laminated sands are shown in Figure 1 of Plate 4 and Figure 1 of Plate 7. Flexures of the pebbles indicate that they were plastic when re-deposited. Except for color, mud breccias of the Grinnell argillites differ slightly from those of Appekunny age and the Spokane specimen of Figure 8. Pebbles commonly are subangular and lie flat in a matrix only slightly coarser than themselves.

Breccias of the *Collenia symmetrica* zone of the Siyeh are found chiefly in siliceous strata 6 to 20 inches thick, best exposed on Cut Bank and Dawson passes. They contain limestone pebbles, which lie at all angles, 25 to 60 mm. wide and 2 to 8 mm. thick. When weathered, they closely resemble the Sheppard stratum of Figure 2 of Plate 3 though the average size of the pebbles is less.

From the 49th parrallel southward, the Goathaunt contains only localized breccias. Some of these, however, are notable because their pebbles consist largely of cross-laminated, gritty dolomite (Pl. 4, fig. 3). Their edges are angular or slightly rounded. Widths range from 2 to 70 mm.; thickness, from 1 to 15 mm.

In Waterton Lakes Park (especially near Alderson Lake), the Goathaunt contains thick breccias in which round or subangular pebbles of quartz and chert are abundant, the former dominating in a ratio of about three to two. Shapes vary widely; the flat pebbles range from 12 to 20 mm. in width and from 2 to 5 mm. in thickness; diameters of others reach 20 mm. As in most pebbly beds of the Altyn, grains fine enough to be classed as sand are not numerous.

In the Granite Park member, breccias are found in calcareous, dolomitic, siliceous, and oölitic beds. They are more abundant in unfossiliferous than in fossiliferous strata, though the algae chiefly associated with them (*Collenia willisii* n. sp.) are found in all except the siliceous breccias. Granite Park oölites, on the Garden Wall and in Hole-in-the-Wall Basin, include cross-laminated strata containing edgewise pebbles. Some fill the interstices between large colonies of *Collenia willisii* n. sp. in position of growth.

Spokane argillites contain numerous breccias of the flat-pebble type, though they are not abundant in red and green beds. Some intergrade with mud-crack layers, as shown by Figure 8. Siliceous Sheppard strata, best developed near Boulder Pass, contain the breccia illustrated in Figure 2 of Plate 3. Pebbles are dolomitic limestone, 1 to 12 cm. wide and as much as 1.5 cm. thick. The breccias lie above beds containing well-defined channels and fillings. Miller Peak mud breccias resemble those of the Spokane and argillaceous Ravalli.

Origins.—Richter [98] and Walcott [99] have observed that mud layers on sand flats may acquire considerable rigidity during the period of low tide; returning waters tear such layers from the underlying sands and break them into small polygons, which are readily transported either seaward or shoreward from the area of origin. Edges are rounded during

[98] Rudolf Richter: *Flachseebeobachtungen zur Paläontologie und Geologie, XVI*, Senckenbergiana, vol. 8 (1926) p. 312-315; Natur und Museum, vol. 59 (1929) p. 77-79, figs. 8-10.

[99] C. D. Walcott: *The Cambrian rocks of Pennsylvania*, U. S. Geol. Surv., Bull. 134 (1896) p. 39.

transportation. In some instances pebbles are promptly covered by silt, the deposits forming strata several inches thick.

Trusheim [100] finds that muds on some tidal flats of the North Sea are made porous by organically generated gases. Snails crawling about the surface break the mud into cakes which are floated by returning tides, often for considerable distances, with consequent rounding of edges. The area of such flakes, or *Tongallen,* ranges from 1 to 10 square centimeters.

Hadding [101] describes many mud breccias ("mud-cake conglomerates, desiccation conglomerates") of Sweden. He apparently accepts transportation and deposition by tides or waves for those whose pebbles lie flat, but he emphasizes falls from shores and subaqueous slides in the orientation of edgewise pebbles. He does not, however, limit edgewise breccias to the results of sliding and falling.

No pebbles in Belt mud breccias indicate fragmentation by organisms; the majority are unmodified or are rounded crack polygons. Probably, however, fragmentation of lime and dolomite muds occasionally was aided by porosity and gases, in the manner described by Trusheim. Some edgewise pebbles in the Goathaunt member (Pl. 2, fig. 1; Pl. 4, fig. 3) seem to be porous and are not recognizable as crack polygons.

Except for minor off-reef deposits, no edgewise breccias in the Belt of the Glacier Park facies indicate falling or subaqueous slipping. Lime-dolomite breccias form strata of uniform thickness and great area; several of them contain undisturbed algal colonies and biostromes. Argillite breccias are equally uniform, though they do not enclose algae. Edgewise breccias whose matrices are sandy are variable in thickness, but they show even fewer traces of sliding than do lime-dolomite deposits.

Both flat-pebble and edgewise mud breccias of the Belt appear to have been transported and deposited by water, generally after fragmentation had been accomplished by cracking of muds. Rhythmic occurrence of breccias, though not conspicuous, is sufficiently distinct to imply periodic disturbance and deposition, while unbroken gradation between slightly modified mud-crack layers (Fig. 8; Pl. 8, fig. 2) and extreme edgewise deposits (Pl. 3, fig. 2) indicates that they represent extremes of one process.

Typically, that process was the return of water to extensive, bare, mud-cracked flats. Gradual return produced breccias which are little more than mud-crack layers with the smallest polygons moved or removed. Throughout the argillaceous epochs, water generally lifted the crack polygons, transported them, rounded their edges, and de-

[100] F. Trusheim: *Eigenartige Entstehung von Tongallen,* Natur und Museum, vol. 59 (1929) p. 70-72.

[101] Assar Hadding: *The Pre-Quaternary sedimentary rocks of Sweden, II,* Lunds Geol.-Min. Instit., Med. no. 32 (1927) p. 60-66; *On subaqueous slides,* Geol. Fören. Stockholm, Förh. (1931) p. 383.

posited them in horizontal positions. During transitional epochs, and in the western Red Gap, water movement was rapid. In some places and seasons, it carried mud polygons to areas of clean but disturbed sand; in others, it mixed polygons and sand together, removing much of the fine mud before the sediment could settle. Both processes produced mud-sand breccias, some with white matrices, and others with pink.

Some lime-mud breccias are of the flat-pebble type; others indicate violent movement of water, in shoals rather than across mud flats. Several breccias in the Altyn, Goathaunt, and Granite Park include pebbles that appear to have been transported from a distance and deposited on flats or algal bioherms, though it is possible that sediments between algal masses were broken, moved, and re-deposited. Other breccias contain supposedly subaqueous mud-crack polygons. Even if deposited *in situ*, they indicate disturbance of shoals rather than re-submergence of exposed flats. That storms were strong enough to disturb submerged bottoms is indicated by the coarseness of land-derived clastics associated with flat pebbles, and by the high angles at which the latter stand.

Clastic mud breccias are consistent with sedimentation on flood plains, in lakes, or in shallow seas. Non-clastic breccias are associated with marine deposition only. A suggestion of marine origin for even clastic breccias is found in the presence of salt crystals and annelid burrows in the breccias or associated strata. That floods and storms were seasonal is indicated by the close association of breccias and rhythmic laminae or varves. Conditions of flooding are discussed under the heading, "Belt Paleogeography."

PEBBLE BEDS, SANDS

Pebbles and sands among precipitated carbonates, some of which are mud breccias, characterize the Hell Roaring and Carthew members of the Altyn and the Goathaunt of the Siyeh near Alderson Lake. Grains range from rounded or subangular quartz and feldspar sand, 0.1 to 2 mm. in diameter, to subangular pebbles measuring 20 mm. Though sand and pebbles generally mingle, some beds and lenses contain only grains less than 1 mm. in diameter. In others, pebbles ranging from 4 to 15 mm. are scattered through otherwise pure dolomites.

In the Hell Roaring member, these clastics form lenses 2 to 3.5 cm. thick or are diffused through massive beds (Pl. 5, fig. 1), in which they constitute 10 to 60 per cent of the total volume. In the Carthew quartzites, best exposed on Mt. Crandell, near Waterton Park, at least 80 per cent of the rock consists of subangular quartz sand.

Abundance and angularity seem unrelated in sand grains, but among pebbles 5 mm. thick or more, angularity is greatest and most prevalent

where the pebbles are widely spaced. At least 80 per cent of the pebbles in compact lenses of conglomerate have well-rounded edges. Spheroidal or regularly ovate pebbles, however, are rare.

A persistent pebble conglomerate occurs near the base of the Singleshot member, on the southward-facing cliffs of Appekunny Mountain and elsewhere. Pebbles reach 10 mm. in thickness, though a large ma-

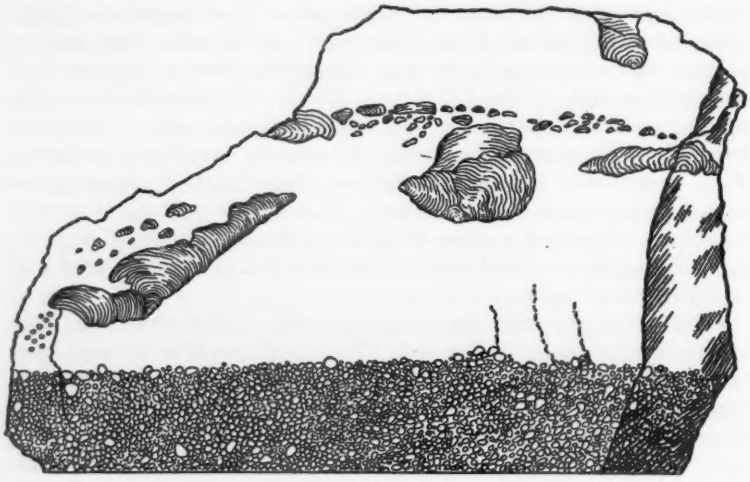

FIGURE 3.—*Pebbles, sands, and algal fragments*

Coarse sand, fine sand (white) and subangular algal pebbles in a bed near the base of the Singleshot. Fine sands contain broken colonies and pebbles of *Collenia columnaris* Fenton and Fenton. × 0.23.

jority are less than 6 mm.; the cement is primarily siliceous. Scattered among the quartz pebbles, especially near the top of the bed, are angular fragments of *Collenia columnaris* Fenton and Fenton and subangular pebbles derived from such colonies (Fig. 3).

Pebbles occur in Goathaunt Siyeh strata of Waterton Lakes Park (Pl. 2, fig. 1). They are flat or angular, rarely rounded; they reach 20 mm. in width and 11 mm. in thickness. Those measuring 1 mm. or more are widely spaced; they are associated with sands in the matrices of mud breccias.

As Daly has shown,[102] many Belt "limestones" are chemical precipitates—not primarily organic deposits or re-worked non-clastics. They contain considerable organic (carbonaceous) matter but little or no clay.

[102] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912) p. 643-675.

Abundant quartz and feldspar sand indicates erosion of primarily crystalline lands, though chert in the Siyeh shows the presence of sediments on them. These clastics have the characters outlined by Twenhofel[103] for arkoses of marine basins adjoining arid regions, where torrential rains are accompanied by floods, strong winds, and disturbance of sea water. McGee[104] has discussed the formation of arkose in the Gulf of California; except for the presence of high tides and strong tidal currents, conditions may represent those of the Hell Roaring and Goathaunt members, where waves and torrential floods must have disrupted partly consolidated bottoms and transported the fragments of feldspar, quartz and chert found in lime-dolomite breccias. Winds alone probably transported much of the sand which forms lenses and massive beds in the Altyn. At times other than those of flooding, sedimentation took place by precipitation of dissolved material.

MUD BALLS

Round, subovate or subangular mud balls (Pl. 12, figs. 1 and 2) occur chiefly in breccias and cross-laminated sands of the Grinnell but also are found in the basal Siyeh and the Spokane (Pl. 4, fig. 2). Some lack internal structure; others are concentrically laminated; a few are both laminated and twisted. They range from 1.5 to 30 cm. in length and 1 to 20 cm. in thickness; in most of them, these dimensions are less than 4 and 6.5 cm. respectively.

Mud balls in recent stream deposits have been studied by Gardner,[105] Haas,[106] and others; those in marine deposits are recorded by Fraas,[107] Grabau,[108] and Richter.[109] The latter, generally called *Tongerölle* or clay boulders, differ from Belt mud balls in having thick encrustations of pebbles or shells, which may be covered by layers of mud. The difference is not fundamental, for it depends upon rolling of balls over fragment- or pebble-strewn shoals, which are not indicated by Belt sediments.

Two explanations for these structures are tenable. One, favored by Grabau and (for large structures) by Haas, is that lumps of mud were broken from shores or banks, rolled about by currents or waves, and deposited. The other, advanced by Gardner, holds that in

"super-concentrated or overloaded [stream] water carrying fine clay particles along a smooth bottom, an adhesion of those particles naturally results. . . . They may

[103] W. H. Twenhofel: *Treatise on sedimentation*, 2d ed. (1932) p. 230-231.
[104] W J McGee: *The formation of arkose*, (abstract) Science, n. s., vol. 4 (1896) p. 962.
[105] J. H. Gardner: *The physical origin of certain concretions*, Jour. Geol., vol. 16 (1908) p. 452-458.
[106] W. H. Haas: *Formation of clay balls*, Jour. Geol., vol. 35 (1927) p. 150-157.
[107] O. Fraas: *Henglin's geologische Untersuchungen in Ost Spitzbergen*, Petermanns Mitt. Geol., vol. 18 (1872) p. 275-277.
[108] A. W. Grabau: *Principles of stratigraphy*, 2d ed. (1924) p. 711-712.
[109] Rudolf Richter: *Flachseebeobachtungen zur Paläontologie und Geologie, XVI*, Senckenbergiana, vol. 8 (1926) p. 305-312.

unite with or without a nucleus. A soft nodule will form, grow, and become rounded by being rotated along its different axes,"[110] gathering new materials as it is rolled. Thus, some nodules grow during transportation; others may either diminish in size (Hass) or increase (Twenhofel).[111]

If all adhesion-balls preserve laminae—which is doubtful—the belt balls belong to both these types. They also may be of either fluvial or marine origin; river-built or corraded balls probably were carried into the basin of sedimentation, while wave disturbance of bottom muds may have produced the overloaded condition postulated by Gardner. The

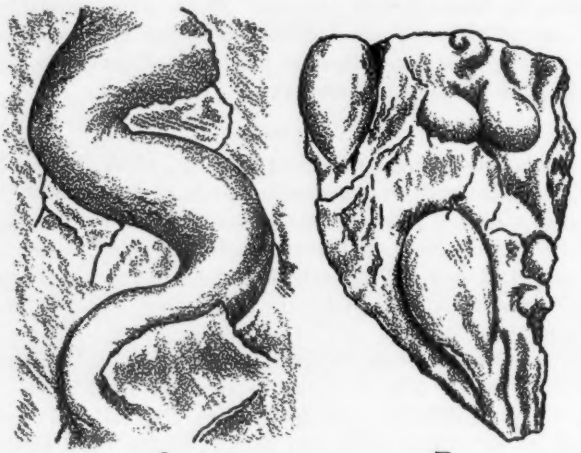

FIGURE 4.—*Channel fillings*

(A) Flexuous channel in argillaceous dolomite (Granite Park), filled with sandy and oölitic material containing small flat pebbles. Adjoining laminae are highly carbonaceous. × 0.2. (B) Channels in red mudstone (Rising Wolf), filled with red mud and sand. × 0.5. (Princeton University Collection.)

writers doubt that clay shore cliffs afforded material for the largest balls, though small ones may have originated through wave-cutting.

In the Rising Wolf, Rising Bull, Granite Park, and Spokane, negatives of irregular depressions and channels are preserved in sandy and argillaceous beds. Those of the type shown in B of Figure 4, and in Figure 2, of Plate 2, seem to have been made on muddy shoals, to which mud balls had been washed, allowing returning waves to erode channels to their lee. While channels grew, the balls shifted, as pebbles and shells shift on modern shores, resulting in elongation and irregularity.

[110] J. H. Gardiner: *op. cit.*, p. 455.
[111] W. H. Twenhofel: *op. cit.*, p. 694.

Associated with channels are negatives comparable to Medina markings called *Fucoides auriformis* and *F. heterophyllus* by Hall;[112] they may represent currents swirling about mud balls. Sandy negatives in dolomites of the Collenia symmetrica zone indicate channel fillings 10 to 30 centimeters in length. Number 8 of the section of that zone on Cut Bank Pass has an irregular, channeled upper surface, overlain by finely laminated dolomites whose layers bend into channels and lesser depressions. Mud balls, however, have not been found with them, nor near the Granite Park channel-fillings of Figure 4, A. In fine-grained siliceous beds of the Sheppard, however, abundant channels are interbedded with edgewise breccias (Pl. 3, fig. 1). Widths range from 2 to 10 centimeters; the patterns suggest that they were produced when widely spaced mud cracks were scoured by currents of receding waves, though small rolled mud balls are found in associated strata.

RIPPLE MARKS

Symmetrical Marks.—Symmetrical ripple marks are found in the Hell Roaring and Carthew members of the Altyn formation, exposures of the Waterton being too limited to reveal them. In the Hell Roaring, they are well developed in thin beds of the Morania zone below Swiftcurrent Falls, where broadly angular marks of Type A (Fig. 5) cross the surfaces

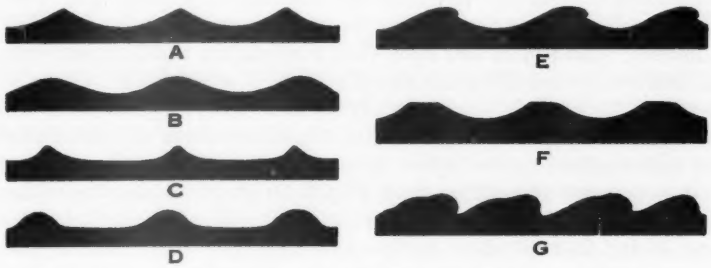

FIGURE 5.—*Diagrammatic sections of symmetrical ripple marks*

(A-D) Original ridges; (E) original ridges rounded and modified by cross-waves or small currents; (F) ridges of type A or B, flattened by cross-waves or currents; (G) ripple marks compressed and steepened by lateral compression.

of thinly bedded, dark-gray dolomites. Wave lengths are 2.5 to 7.5 mm.; amplitudes approximate 12 mm. On Roes Creek, in the St. Mary Valley, similar marks also are found in the Morania zone. Above these lie thickly bedded, sandy dolomites, some of whose surfaces bear marks of Type C (Fig. 5), with wave lengths of 20 to 40 cm. and amplitudes of 6 to 16 mm. Troughs between the ridges are almost flat and bear a few traces of second-

[112] James Hall: *Palaeontology of New York*, vol. 2 (1852) p. 7, pl. 3, figs. 3-4.

ary ridges, either parallel or oblique. Near the top of the Hell Roaring member, on Appekunny Mountain, thin argillaceous dolomites bear small ripple marks of Type D, with wave lengths of 12 to 20 mm. and amplitudes of .5 to 6 mm. They resemble the ripple marks illustrated in Kindle's Plate 21, B,[113] formed by wave action in water 4 inches deep, though the ridges may have been rounded by slipping of beds near the secondary Lewis fault. Obscure ripples of Type B are seen in sandy beds of the upper Carthew northwest of Vimy Peak, Waterton Lakes Park.

Symmetrical ripples of Types B and C, in basal Appekunny (Singleshot) quartzites, show wave lengths of 3.5 or 9 cm. and amplitudes generally less than 12 mm. They are indistinct and irregular; some are modified by deformation. Ripples are few in coarse sands and sandy argillites; in fine-grained argillites of the Appistoki, they are very rare. They also are poorly developed in the Scenic Point member, though some red and pinkish mud-cracked strata show indistinct ripples of Type A.

Ripple marks are abundant in the quartzitic beds of the basal Grinnell (Rising Bull). Rippled layers range from sandy mudstones and mud breccias to white quartzites, those most abundantly marked being pink argillaceous quartzites. Marks are chiefly of Type A, with wave lengths of 25 to 100 mm. and amplitudes of 8 to 20 mm. Some beds, however, bear marks of Type E—symmetrical ripples originally of Type A, but with crests rounded by currents or waves along the furrows. The writers have watched similar ripples form on sandy shores, at times of tidal ebb and flow. Such ripples also form when wavelets, too small to build ridges of their own, sweep along thin sheets of water, deepening the furrows and rounding the crests of marks already formed. Because pronounced tidal action in the Belt sea seems doubtful, the writers favor this latter origin for such modified ripples in that series.

A second type of modified mark (Fig. 5, G) shows peculiarities of diastrophic origin. Sandstones and interbedded argillites in both Rising Wolf and Rising Bull members contain numerous beds that resemble overturned negatives of angular wave ripples. All such beds, however, lie in zones of slipping, oblique faulting, and folding, as on Ptarmigan Wall and in Baring and Roes basins. Where fresh, their surfaces bear indistinct slickens with green, apparently reduced argillites which are crumpled into the furrows. The "negatives" are the results of slipping of quartzite beds along argillaceous partings, with thickening of the lower quartzite accompanied by narrowing of the original furrows and rounding of ridges. Some show horizontal displacement and bending of the ridges, which curve irregularly and join along lines of maximal yielding or pressure.

[113] E. M. Kindle: *Recent and fossil ripple-mark*, Geol. Surv. Canada, Mus. Bull. 25 (1917) 121 pages. Because of its availability and excellent illustrations, this publication will be used as a standard of comparison for Belt ripple marks.

Ripple marks are common in quartzites and sandy dolomites in the Collenia symmetrica zone of the Siyeh formation. The most common belong to Type A, with wave lengths of 5 to 20 cm. and amplitudes of 10 to 12 mm. for the small and 20 to 32 mm. for the large ripple marks. At Ptarmigan Wall, greenish, sandy dolomites bear comparable ridges of Type C, which grade into interference patterns.

The Goathaunt member is poor in ripple marks, though a few of Type A, with wave lengths of 3 to 6.5 cm., are found between Logan Pass and the *Collenia frequens* reefs or bioherms. None compares in size or distinctness with those of the dark-gray, fine-grained Altyn of the Swiftcurrent Valley. Marks of Type A and Type B occur in cross-laminated sandy and oölitic beds of the Granite Park. They are poorly developed, however, and cover small areas.

Ripple marks abound in red and green sandy argillites of the Spokane; those of the red strata are best exposed west of Swiftcurrent Pass and on the Garden Wall trail to Ahern Pass. They are dominantly of Type A, with long flexuous ridges and furrows of uniform width. Secondary ridges are not prominent, though a few strata show distinct oblique ones. In some marks, the ridges break up and others are inserted, as in the Edmonton stratum of Kindle's Plate 24, A. Amplitudes range from 20 to 75 mm., though the majority lie between 25 and 45 mm.

Small ripple marks are abundant on blocks of red, green, and buff-brown Spokane argillites and sandy quartzites in the moraine of Clements Glacier, near Logan Pass. Ripples in red beds are sharper and smaller than those in green, affect finer laminae, and are more uniformly abundant. Buff-brown strata bear few and small ripples. As in the Ravalli, strata showing thinnest laminae and finest mud-cake conglomerates show the fewest and poorest ripples. In some red, sandy layers, wave marks are modified by cross-markings of current origin, giving patterns comparable to those shown on Kindle's Plate 15.

Ripple marks in the Sheppard are confined to the few basal quartzites, where they are much like those of similar beds in the basal Siyeh.

Ripple marks are abundant in all observed members of the Miller Peak group. In the Kintla, most of them belong to Type A, closely resembling the finer marks of the red Spokane. Extensive beds of argillaceous sandy quartzite almost duplicate the rippled and cracked Edmonton sandstone illustrated by Kindle's Plate 24, A. Such rippled layers rarely contain casts of salt crystals.

In the Roosville, wave lengths of ripple marks reach 12.5 cm., though amplitudes rarely exceed 25 mm. Ridges are sharply angular (Type A) or show slight re-working of Type E. Rill marks are common in some beds.

The Mt. Rowe, in both Waterton Park and the Flathead Range, contains abundant ripples differing slightly from those of the Kintla and Spokane. They are more uniformly linked with mud cracks.

Interference Patterns.—Except for a few in the Grinnell and Spokane, interference patterns characterize ripple marks of wave, rather than current, origin. The lowest well-developed examples are found in the Rising Wolf member, where reddish-brown, argillaceous quartzites bear ripples of Type A. At a higher horizon, thin-bedded, rose-red, argillaceous and sandy quartzites show exceptionally fine interference ripples, also of Type A, in which wave lengths reach 50 mm. and amplitudes 12 mm.

Similar, though coarser and less distinct, patterns are seen in the Collenia symmetrica zone. Its most distinct interference ripples, however, belong to Type C; in them, flat furrows and sharp ridges meet in reticulate, rather than subquadrangular, patterns. Wave lengths reach 15 cm. but generally are less than 10; amplitudes reach 2 cm. Smaller marks belong to Type A or Type C, with irregularly fluted patterns.

A persistent zone of interference ripples lies in the Spokane, above the Purcell lava. Near Granite Park, it consists of pale-green to pink quartzites in beds 1 to 15 inches thick; they bear sharply angular marks of Type A, closely resembling the Carboniferous marks of Cape Breton, illustrated in Kindle's Plates 30, A and 31, B, and the casts shown in his Plates 22 and 23, C. Kindle finds such marks to be:

"developed under shallow water in which the ordinary wave generated by the action of the wind on the surface is split up into two or more sets of oscillations moving in different directions. The gradual movement of fine sediments . . . results in the coarse cell-like structure. . . ."[114]

Such splitting of waves is commonly caused by piles, projecting rocks, and breakwaters; since comparable structures are not traceable in the Belt series, one must assume that either shifting wind or friction of slightly submerged bottoms produced this result. In some cases, one set of ripples crosses and partly breaks up another, as if superimposed by later waves at approximately right angles to those producing the first set.

Thin, greenish strata, best exposed on Rosenwald Point, north of Granite Park, bear interference marks resembling the "tadpole nests" of Hitchcock,[115] discussed and illustrated by Kindle.[116] Furrows are replaced by subquadrangular to round, concave depressions separated by flat longitudinal bands and narrow cross bars. Unlike the examples illustrated by Kindle, however, the arrangement of these bands and bars is regularly

[114] *Op. cit.*, p. 35.

[115] Edward Hitchcock: *Ichnology of New England* (1858) pl. 1, fig. 1.

[116] E. M. Kindle: *An inquiry into the origin of "Batrachioides the antiquor" of the Lockport dolomite of New York*, Geol. Mag., dec. 6, vol. 1 (1914) p. 158-161; *Recent and fossil ripple-mark*, Geol. Surv. Canada, Mus. Bull. 25 (1917) p. 34-36; pls. 23 A, 30 B.

quadrangular, with re-curved edges overlapping the depressions. Apparently, the whole was produced from an originally regular quadrangular ripple pattern re-worked under shifting winds by waves, which flattened and re-deposited the material of the ridges. Some of this re-deposited material is visible in the depressions. This conclusion is in order with Kindle's:

"Successive observations of one set of interference ripples, continued for three days, [which] have . . . shown that aging of the impressions . . . tends to alter angular partitions to rounded ones. . . ." [117]

The writers have observed modification of ripples of Type A into Types B and C.

The zone of the interference ripples in the Spokane formation is persistent. Specimens are found in drift-talus of Mt. Clements, near Logan Pass; in talus near Mt. Kipp, and in place near Boulder Pass, over a total distance of about 25 miles.

Asymmetrical Marks.—The writers [118] once said that current ripple marks were prevalent in the Belt series of Glacier Park. Studies in 1932 and 1934 showed this statement to be erroneous; in most formations, asymmetrical ripples are rare. In only the Rising Bull member of the Grinnell are they common, and even there they do not predominate. They are strong flexuous ripple marks with wave lengths of 20 to 35 cm. and amplitudes of 2.5 to 5 cm. When ridges are rounded and the furrows made angular by deformation, they are almost indistinguishable from Type G of Figure 5.

Beds of small, irregular current ripples comparable to those of Kindle's Plate 21, A, occur in the Rising Bull, the Collenia frequens zone, and the uppermost Spokane. Wave lengths reach 15 cm., amplitudes 2.5 cm.

Spokane red beds have indistinct current ripples modified by waves, as well as wave ripples modified by currents. There also are suggestions of imbricated wave markings like those of Kindle's Plate 19, B, though with rounded sides and apices and general lack of definition. Their association with sharp marks suggests that these characters are of primary origin, rather than due to secondary wear or "aging."

Origins—Ripple marks in the Glacier Park facies are dominantly symmetrical (wave-made), with zones of interference marks. All are consistent with sedimentation in shallow—often very shallow—water. Many ripple marks seem to have been buried without emergence, but, in others, mud cracks and salt crystals indicate emergence and desiccation.

Thin zones of ripple marks extend over considerable areas and across

[117] E. M. Kindle: *Recent and fossil ripple-mark*, Geol. Surv. Canada, Mus. Bull. 25 (1917) p. 35.
[118] C. L. Fenton and M. A. Fenton: *Algae and algal beds in the Belt series of Glacier National Park*, Jour. Geol., vol. 39 (1931) p. 679-680.

distances of at least 25 miles; thick ones persist throughout at least 1800 square miles. In the former, the marks show approximately uniform orientation, attributable to the limits of a long narrow basin if it is supposed (a) that winds were exceptionally stable, and (b) that they blew at almost right angles to the basin's length. Hyde [119] has shown the improbability of such uniformity, but he finds that superficially similar control can be exercised "either by a shore line or water so shallow as to bring waves into adjustment parallel to this shore line, or . . . to the contours of the sea floor."

It was not possible to make detailed plottings which would give data for orienting Belt shore lines. In general, however, wave ripple marks trend N. 25° to 55° W., especially in the Rising Bull member and the Spokane formation. Axes of such current ripples as were examined strike N. 70° to 80° E.—almost at right angles to the nearest wave ripples. This suggests that the latter were controlled by a shore line trending northwestward, with considerable irregularities, while currents swept southeastward along that shore.

Ripple marks, however, tell little as to whether that shore bordered a sea or a lake. Kindle [120] has contrasted current and wave ripple marks, finding the former to be primarily estuarine or marine and the latter lacustrine. His conclusions, however, apply to typical seas of the present, from which those of the Belt basin must have differed in shallowness and in almost complete freedom from tidal currents and scour.

MUD CRACKS

Desiccation Cracks.—As with ripple marks, no mud cracks have been observed in the Waterton member. Mud cracks also are rare in the Hell Roaring and Carthew members, being represented only by incomplete flexuous cracks 50 to 100 millimeters long, in sandy beds near the Narrows on St. Mary Lake, and by crack-like markings at the northern foot of Vimy Peak.

Irregular cracks enclosing convex polygons occur in the basal Appekunny (Singleshot), chiefly in impure quartzites capped by thin laminae of argillite. Some of these beds were rippled before cracking.

Mud cracks are abundant in the Appistoki, especially in the purer argillites. Polygons reach 40 cm. in diameter, though the majority are small—less than 4 cm. in diameter, with smaller pieces ranging from 1 to 0.1 millimeter. Most of these deposits, however, are so closely linked with flat-pebble mud breccias that they were considered under that heading.

[119] J. E. Hyde: *The ripples of the Bedford and Berea formations of central and southern Ohio, with notes on the paleogeography of that epoch*, Jour. Geol., vol. 19 (1911) p. 257-269.

[120] E. M. Kindle: *Diagnostic characteristics of marine clastics*, Geol. Soc. Am., Bull., vol. 28 (1917) p. 913-915.

Mud cracks characterize the massive argillites of the Scenic Point member, being best exposed near Twin Falls and in Cobalt Basin, in the Two Medicine region. These cracks, 1 to 4 cm. wide, enclose roughly quadrangular, flat polygons, 20 to 60 cm. in width. These polygons are divided by secondary cracks, 1 cm. or less in width, into polygons whose diameters range from 5 to 10 cm.

At the type locality, on the Scenic Point trail, massive beds give way to thinly bedded, green, brown, pink, purplish, and red argillites, sandy argillites, and sandstones. In the argillites, some of the cracks are only 1 mm. wide, enclosing flat, quadrangular polygons of variable size: those of one specimen measure 20 by 35 mm., though the majority are larger. Other argillites are interbedded with white or brown sand; in them, cracks 2 cm. wide surround variously shaped polygons, some of which are as much as 25 cm. long. Though surfaces are irregularly warped, edges are sharply downcurved, as shown in Figure 2 of Plate 7. Many cracked layers, with or without sand, grade into mud breccias.

Where sand is present in superjacent layers, it generally makes small, sharp pits in cracked surfaces. This may mean that the mud cracked and was buried before it had time to dry; it may merely indicate that returning waters dampened the cracked, hardened mud sufficiently for it to take the impress of sand grains. If the latter is true, burial was accomplished so promptly that the polygon edges remained sharp.

Mud cracks are abundant in both sandy and argillaceous beds of the Rising Wolf, in the talus at Cobalt Lake, at No-name Lake, below Pumpelly Pillar, and elsewhere. They range from minute cracks 1 mm. wide, enclosing polygons about 15 mm. in diameter, to cracks 15 to 35 mm. wide, enclosing polygons 20 to 40 cm. in length, whose surfaces are either flat or convex.

Though large polygons are enclosed by wide cracks, the latter also surround polygons less than 4 cm. in width. Sandy beds, especially in the Rising Bull member, bear negatives showing radiation of three incomplete cracks from a common center. They do not maintain equal width or attain equal length; angles range from 70 to 160 degrees instead of the theoretical 120.

Related to these are incomplete cracks found in regularly laminated ledges of the lower Red Gap in Roes Basin, near St. Mary Lake. A typical pattern, determined by tracing, is shown in Figure 7; the smallest cracks are 0.2 to 0.4 millimeter in depth. Polygons are flat or slightly warped, with slightly upturned edges. Fragments, which suggest minute mud-crack polygons dropped into the cracks, prove to be only chips broken from the edges of separating polygons.

Typical cracks in the Red Gap member resemble those in the massive ledges of the Scenic Point. Large polygons are divided by secondary and

tertiary crack systems; all polygons are flat or slightly downcurved at the margins. In several places, the primary cracks are so distinct as to suggest the "joints" which Kindle [121] finds associated with recent cracks; such cracks commonly control joints in the Grinnell and Spokane formations and the Scenic Point member. In many places, cracks have been compressed and straightened by lateral pressure, though these are most common in brown beds of the Scenic Point and Spokane.

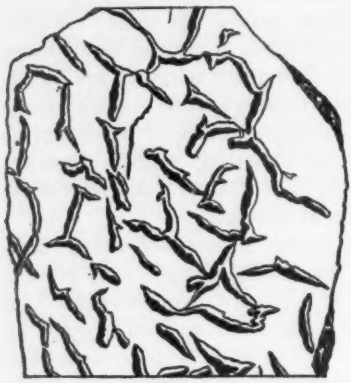

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FIGURE 6.—*Negatives of incomplete mud cracks*

Rising Wolf member of the Grinnell formation, at Cobalt Lake. × 0.7.

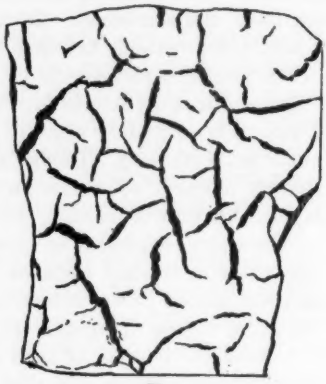

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FIGURE 7.—*Incomplete mud cracks in argillite*

Lower Red Gap member of the Grinnell formation, Roes Basin. × 0.6. (Princeton University Collection.)

The Rising Wolf member physically resembles the Rising Bull and shows similar alternation of argillites and cross-laminated sandstones, grading into mud breccias. Many cracks are coarse, though they may enclose polygons less than an inch wide. Many slabs show primary and secondary cracks enclosing downcurved polygons, associated with rain and hail prints.

Cracks are uncommon in the basal Siyeh. Near the middle of the Goathaunt member, they become numerous, the polygons generally consisting of black limestone and the fillings of dark dolomite. In size, convexity, and shapes, they closely resemble those shown in Figure 2 of Plate 7. Argillites in the Goathaunt contain flat polygons which generally are displaced and therefore rank as breccias. Schofield [122] illustrates com-

[121] E. M. Kindle: *A note on mud-crack and associated joint structure*, Am. Jour. Sci., 5th ser., vol. 5 (1923) p. 329-330.

[122] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) pl. 16.

plete mud cracks in brown and purple Siyeh argillites of the Cranbrook region; they show convex small polygons and large ones which are down-curved only marginally. Flat polygons and large cracks filled with breccia and dolomite, from argillaceous beds of the upper Siyeh (Granite Park), are shown in Figure 1 of Plate 6; they bear abundant impressions of salt crystals.

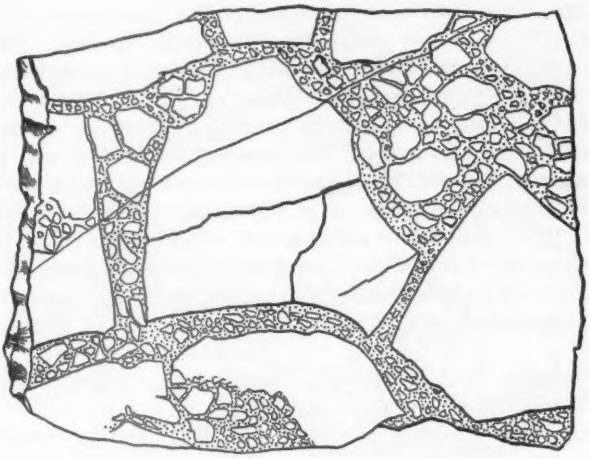

FIGURE 8.—*Mud cracks grading into mud breccia*
Large polygons shifted; small ones partly removed. Spokane, Clements Glacier. × 0.6.

Mud cracks of the Spokane formation occur chiefly in green and brownish argillites. Like many cracked argillites of the Grinnell, their polygons show up-curving and down-curving of edges, caused by maximal shrinkage in medial portions of the drying layers, with consequent marginal thickening. Typical examples are shown in Figure 2 of Plate 6. In some green strata underlying *Collenia undosa* Walcott, polygons are highly convex. Cracks are few in the red, sandy, abundantly rippled strata exposed at many localities from Logan Pass northward.

Except for those in sandy strata, mud cracks of the Sheppard appear to be subaqueous and are discussed under that heading. Those in the Roosville rarely are complete; if complete, they enclose narrow, irregular polygons. Cracks in the Kintla and higher members of the Miller Peak differ little from those of Spokane strata.

Subaqueous Cracks.—Many beds in the Goathaunt member, and especially in the Sheppard formation, consist of crumpled dolomites and

limestones which superficially resemble "molar-tooth" segregates. They are not arranged obliquely, however; on weathered bedding planes, the dolomite generally shows angular, irregularly warped polygons, embedded in amorphous limestone or mud breccia (Pl. 8). Where these structures grade into "molar tooth" (Pl. 4, fig. 4), they do so through deformation of cracks and fillings already lithified.

Virtually unmodified structures of this type occur in laminated off-reef beds of the large *Collenia frequens* reef on the Going-to-the-Sun Highway (Pl. 17); they are continuous with regular laminae. Downbent laminae and layers also grade into broken laminae and crumpled polygons closely resembling those shown in Figure 1 of Plate 8. Similar continuity of cracked and distorted layers with flat-lying layers is seen at other localities and horizons. From them, these conclusions are reached:

(1) Alternations of dolomite and lime in these structures must be the result of original deposition, or of replacement while muds were still plastic. This is essential to cracking and transportation (Pl. 8, fig. 2).

(2) Cracking of dolomites occurred while laminae beneath them were soft enough to be pierced by downbent edges of polygons, or even to rise and fill the mud cracks, for such filling is indicated by numerous flow lines.[123]

(3) Shrinkage and cracking were subaqueous, for neither reefs nor algal colonies indicate repeated emergence.

(4) Cracking continued over long periods, greatly complicating the original polygons and allowing calcite to fill the irregular fractures.

(5) Cracking of lime layers, if it occurred, was so unusual that its results have not been reliably determined.

No explanation for this subaqueous cracking is apparent; it did not arise from freezing, like subaqueous cracks observed by Moore,[124] nor in the manner described by Twenhofel.[125] The latter demands that saturated particles settle upon unsaturated ones; cracks open as the lower lamina absorbs water and expands. The Belt cracks indicate the reverse of this—contraction of upper (dolomite) laminae at a rate greater than that of the underlying lime. This is consistent with the presence of cracks in dolomite laminae whose polygons are slightly curled. Predominance of limestone among flat pebbles may indicate that the dolomite mud was

[123] Depression and compression of layers below reef cores, and even individual algal colonies, indicate that muds remained plastic to depths of 5 feet or more for periods ranging from 80 to 1000 years or more. Dr. R. M. Field (oral communication) reports similar plasticity of lime muds near Andros Island, Bahamas, and suggests that it lasts until deep burial produces lithification. Conditions in the Bahama shoals, as described by Maurice Black [*The algal sediments of Andros Island, Bahamas*, Royal Soc. London, Philos. Tr., ser. B, vol. 22 (1933) p. 165-167, 177], resemble those postulated for carbonate epochs of the Belt.

[124] E. S. Moore: *Mud cracks open under water*, Am. Jour. Sci., 4th ser., vol. 38 (1914) p. 101-102.

[125] W. H. Twenhofel: *Development of shrinkage cracks in sediments without exposure to the atmosphere*, Nat. Res. Council, Rept. Comm. Sedim. (1925) p. 75-76.

deficient in tensile strength, though there are exceptions to this rule (Pl. 4, fig. 3).

Resemblance to Black's [126] figures and description of alga-filled mud cracks suggests that these subaqueous polygons were covered and strengthened by sheets or mats of non-calcareous algae. In most strata, limestone layers and crack fillings are darker than the shrunken dolomites,

FIGURE 9.—*Vertical section through filled subaqueous mud cracks*

Black, carbonaceous limestone; white, buff-weathering, gray dolomite. Siyeh, moraine at Iceberg Lake, Glacier National Park. × 0.6. (Princeton University Collection.)

which indicates excess carbon during deposition of calcite. If that calcite merely caught on the mucilaginous mass of an algal mat, it might not show lamination, or lamination might be lost readily, as it is in some of Black's material. If factors destroying lamination, consistent with modern algal deposits, operated, they prevented or removed reliable indications of algal growth upon polygons and in ramifying cracks.

IMPRINTS, PITS

Round prints attributed to rain drops or stranded gas bubbles are found in thinly laminated blue-green argillites of the upper Appistoki member on the Scenic Point trail. Diameters range from 5 to 8 millimeters; depths are less than 0.5 millimeter. There are no tubes leading to them; on a slab, 2 millimeters thick, the upper surface bears large pits and, on the

[126] Maurice Black: *op. cit.*, p. 173.

lower, there are negatives of abundant small oblique and conical pits. They closely resemble pits whose formation may be observed when hard-driven sleet falls upon plastic mud. In the late Appistoki epoch, most of the inferred sleet was driven by northwesterly to southwesterly winds.

Prints, 2.5 to 4 mm. in diameter and 1 to 1.6 mm. deep, mark many sandy beds in the Rising Wolf member. Most of them are slightly oblique and indicate rain drops rather than sleet or ascending gas bubbles. Larger rain prints are abundant in some Red Gap argillites and in argillaceous quartzites of the Rising Bull member; they commonly coalesce, like some of the rain prints studied by Twenhofel.[127] In both members, there are many oblique pits, 3 to 5 mm. in diameter and 3.5 mm. in depth, with slight ridges on the hanging margins; the end of each pit is cup-shaped, not angular. Such impressions are attributed to hail stones driven by westerly storms.

Both rain and hail marks, resembling those in the Grinnell, are found in the Kintla and Mt. Rowe members of the Miller Peak formation, chiefly in argillaceous sandstones or quartzites. These marks indicate emergence of broad mud and muddy sand flats, supporting the interpretation of their cracks as the results of desiccation rather than of subaqueous shrinkage.

Pit and mound structures, developed by currents accompanying the flocculation of clay in salt water, have been described by Kindle.[128] Similar structures are found in argillaceous quartzites among mud breccias of Rising Wolf age, at Cobalt Lake, the foot of Pumpelly Pillar, and near Gunsight Pass. The central pits are 1 to 4 mm. wide and 3 to 6 mm. high. With them are "pin-head depressions," suggesting minute rain prints, whose association with the mounds indicates common origin in salty muds.

SALT CRYSTAL CASTS

Salt crystal casts of Belt age have been figured by Daly[129] and Schofield[130] and mentioned by Bauerman.[131] They are found chiefly in the Kintla, Roosville, and Mt. Rowe, though the specimen figured by Schofield is from the Gateway (= Sheppard, Helena). Salt crystal impressions are abundant in a few strata of the Spokane, Granite Park, and

[127] W. H. Twenhofel: *Impressions made by bubbles, rain-drops, and other agencies*, Geol. Soc. Am., Bull., vol. 32 (1921) p. 359-371.

[128] E. M. Kindle: *Small pit and mound structures developed during sedimentation*, Geol. Mag., dec. 6, vol. 3 (1916) p. 542-547; *Diagnostic characteristics of marine clastics*, Geol. Soc. Am., Bull., vol. 28 (1917) p. 909-910.

[129] R. A. Daly: *Geology of the North American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) pl. 11.

[130] S. J. Schofield: *op. cit.*, p. 36, pl. 17.

[131] Hilary Bauerman: *Report on the geology of the country near the forty-ninth parallel of north latitude west of the Rocky Mountains, from observations made in 1859-61*, Geol. Surv. Canada, Rept. Prog. 1882-83-84 (1885) B, p. 25.

Coathaunt, are sparcely present in a few Rising Bull and Rising Wolf strata, but have not been found in the Appekunny or Altyn.

The Kintla crystals (Pl. 2, fig. 3) commonly are cubical, obliquely embedded in red argillite or argillaceous sandstone; their thicknesses range from 2 to 22.5 mm. There also are "basket" and "needle" crystals containing 3 or 4 visible rods, of which one may be twice or three times as long as the others. Roosville crystals are similar to these, but rarely exceed 4 mm. in thickness. Cubical crystals, 2 to 8 mm. thick, are found in some horizons of the Spokane, but they generally are lacking. Crystals of the Granite Park are cubical or elongate and measure 2 to 5 mm. (Pl. 6, fig. 1); they are found in purplish, dolomitic, thickly stratified argillite having large, flat, mud-crack polygons. Impressions of similar crystals, 1.5 to 3 mm. long, are abundant in gray dolomitic limestones of the Goathaunt member, near Indian Pass. Crystals of the Grinnell are indistinct cubes, sparsely scattered through a few strata.

Scarcity of salt crystal casts in Rising Wolf and Rising Bull strata bearing highly convex mud-crack polygons may be explained in two ways. First, those beds suggest flooding by fresh waters, the mud cracks representing periods of low water and desiccation between floods. In those periods, the mud may have become salty enough for convex polygons to develop, without reaching the concentration necessary for crystal formation. Second, crystals may have developed, only to be dissolved in the next flood. The latter hypothesis requires that crystals formed on mud or muddy sand, but either left no impressions or made impressions so indistinct as to be readily destroyed. This seems to be true of some strata of the Grinnell and Kintla, but not of the Siyeh, where sharp impressions are found both above and below stratification planes. The first hypothesis, therefore, seems the more likely, with the second subsidiary but periodically effective.

In general, the presence and abundance of salt crystals suggest periodic increase in salinity of water, culminating in the Kintla and Roosville. Considered alone, the crystals suggest marine (including estuarine) or salt-lake deposition. Those of the Siyeh join with brachiopods in the equivalent Newland[132] to indicate marine origin; the close similarity of Siyeh and Sheppard gives crystals in the latter formation the same significance. Those of clastic formations are consistent with either marine or lacustrine deposition.

OÖLITES

Oölites, whose grains range from 0.1 to 3 millimeters in diameter, occur at several horizons in the Piegan group. The lowest is the Collenia sym-

[132] C. L. Fenton and M. A. Fenton: *Walcott's "Pre-Cambrian Algonkian algal flora" and associated animals*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 616.

metrica zone, where thin beds of sandstone or sandy dolomite contain abundant black oölite grains. Primarily these are carbon-stained calcite, but in many of them the calcite is replaced by silica. These oölites are not intimately associated with algae.

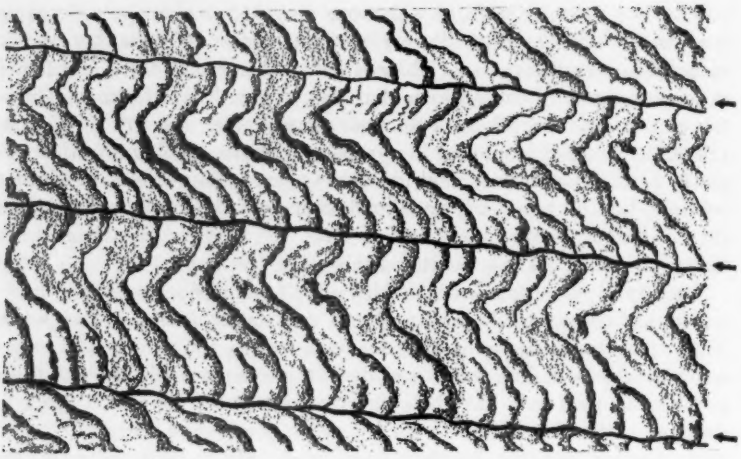

FIGURE 10.—*Orientation of "molar tooth" segregation structures between planes of movement*

Direction of movement is indicated by arrows. Goathaunt member of the Siyeh formation, west slope of Mt. Wilbur.

Buff-weathering dolomites of the Goathaunt member, near Indian Pass, contain abundant granules of black or dark-gray limestone without perceptible structure. Outlines of the larger granules are subangular, suggesting fragments of partly consolidated mud or of algal colonies. Some, however, may be oölitic.

Several beds in the Granite Park member, at Logan Pass and elsewhere, contain concentric oölite granules, chiefly calcitic. Some surround colonies of *Collenia willisii* n. sp.; except for dolomitic cement, they constitute the matrix. In most strata, however, apparent oölites prove to be round, ovoid, or irregular fragments of both calcite and dolomite, with interbedded sand grains, 1 to 4 millimeters in diameter. Strata so constituted commonly show cross-lamination or even ripple marks, and their algal colonies appear to be eroded.

Thin beds of dolomitic oölite are found in the Sheppard formation, among siliceous strata.

SEGREGATION STRUCTURES

Many horizons in the Altyn, Siyeh, and Sheppard bear lenticles, cylinders, and other structures of limestone or dolomite, whose segregation occurred long after induration. The most familiar of these first was

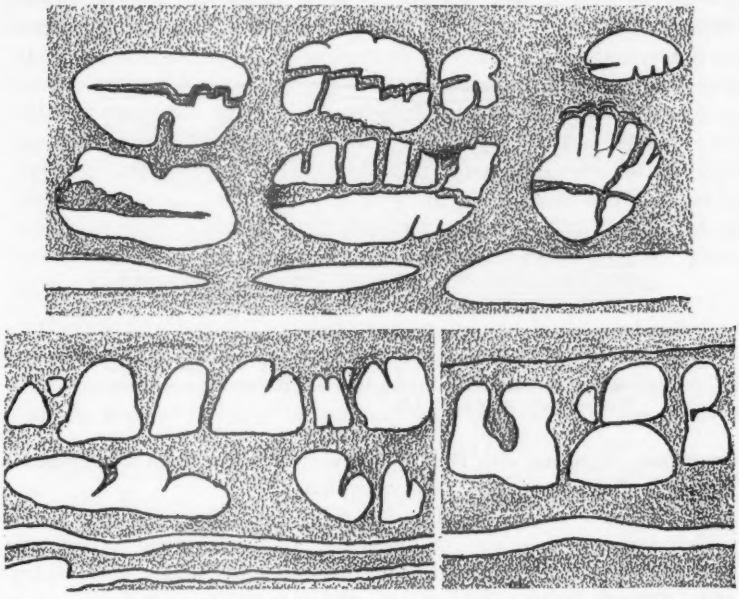

FIGURE 11.—*Natural sections of segregation structures*

Lime (white) in dolomite (stippled). Upper Goathaunt member of the Siyeh formation, near Piegan Pass. × 1.

mentioned by Bauerman as "impure limestone in which the carbonate of lime is intermingled with argillaceous [= dolomite] particles or folds resembling the markings on the molar tooth of an elephant."[133] Daly[134] also used the term "molar tooth" and assigned the structures to segregation along cleavage planes at high angles to the bedding, the resulting laminae being crumpled where lateral pressure was great. Figure 10 shows "molar tooth" of exceptional uniformity between slickened planes. Figure 4 of Plate 4 shows a weathered section at right angles to the plane of Figure 10.

[133] Hilary Bauerman: *op. cit.*, p. 26.
[134] R. A. Daly: *op. cit.*, p. 73-76, pl. 10, lower, pl. 14.

Imperfect "molar tooth" structures are found in the Altyn formation and the Collenia symmetrica zone, but their greatest development comes in the Goathaunt, the Sheppard, and some beds of the Granite Park. Except where subordinate to supposedly subaqueous mud cracks, they bear out Daly's explanation of their origin.

Associated with "molar tooth" in some strata are steeply inclined laminae of dolomite, intercalated with flat-lying laminae and lenticles of

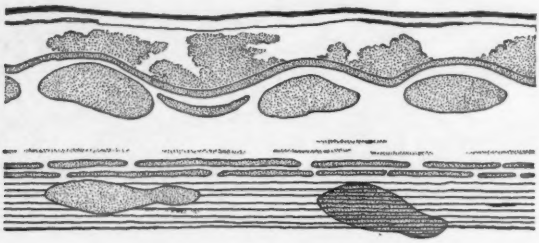

FIGURE 12.—*Segregation structures*

Dolomite (lines and stipple) in limestone (white). One dolomite layer follows ripple marks. Hell Roaring member of the Altyn formation, near Waterton Park, Alberta. × 0.46.

limestone. Agreeing with Daly,[135] the writers assign them to segregation along parallel, non-crumpled cleavage planes.

Many strata in the Hell Roaring, Siyeh, and Sheppard contain secondary bodies of dolomite and limestone. In strata primarily limestone, dolomite is segregated into nearly pure blue-gray bodies whose shapes range through nodules, flat lenticles, and rods to irregular masses not of characterizable shape. Bedding or lamination planes are the chief loci of segregation; such planes are continuous through the resulting bodies, which may intergrade with continuous laminae discussed as original products of sedimentation.

In upper Goathaunt strata, along the trail leading eastward from Piegan Pass, elongate nodules of limestone lie in dolomite, but are cut vertically and horizontally by seams of that rock until they suggest septarian concretions. Near them are many smaller rods of limestone, which closely resemble the structures named *Greysonia* and *Copperia* by Walcott, but which appear to be products of segregation and crumpling under lateral pressure.[136] The Siyeh exposures contain typical "molar tooth" layers, as well as others which seem to be modified mud cracks. In primarily calcareous strata, dolomite becomes the segregate. Figure 12 shows

[135] *Op. cit.*, p. 74, pl. 10, upper figure.

[136] C. L. Fenton and M. A. Fenton: *op. cit.*, p. 612-614.

primary segregation products in both laminae and lenticles. Such structures are common in the Hell Roaring member of the Altyn, on the Bertha Lake trail, near Waterton Park, Alberta.

RHYTHMS IN SEDIMENTATION

Prevalence of Rhythms.—Throughout the Glacier Park facies, sedimentary changes are dominantly rhythmic. In the Altyn formation there are alternations of limestone and dolomite, of abundant and scanty carbon, of argillaceous and pure dolomite; similar rhythms characterize most of the Siyeh and the Sheppard. Laminae and strata of the dominantly argillaceous formations show alternations in color, texture, and apparent conditions of deposition. This is especially true of transition members such as the Rising Bull, in which alternations of red mudstone and greenish to white quartzites are conspicuous. Even ledges formed chiefly by algae show marked and abundant rhythms (Pl. 9), which, at another extreme, show in periodic repetition of mud breccias.

Carbon Rhythms.—The rhythms most readily interpreted are those of abundantly and slightly carbonaceous laminae. The regularity of their occurrence, in formations containing both massive calcareous algae and the frondose *Beltina*, suggests at once that they are the result of periodic abundance and scarcity of organisms, probably algae.

Such fluctuations characterize modern algae and other plants. The eel-grass, *Zostera*, is seasonal; Raymond and Stetson[187] have used it to explain potentially rhythmic deposits in Massachusetts Bay. Planktonic plants fluctuate seasonally, and with them the animals for which they provide food, the controlling factors apparently being temperature and light.[188] In tropical and subtropical seas, rainy periods, monsoons, shifting currents, and kindred secular factors directly affect the plant life of the water and cause it to fluctuate in abundance.

The Belt basin lay so far north (46 to 52 degrees) that light reaching it fluctuated seasonally, as does that of Puget Sound or Passamaquoddy Bay today. Its bottom, even in periods of dolomite or lime deposition, was within the zone of plant growth and of effective action by small waves —hence, in the shallower part of the photic zone. Unless the climates were more equable than may be inferred from the limited extent of Belt seas, the basin was affected by seasonal changes in temperature. There also is evidence, already discussed, of periodic floods which modified salinity, alkalinity, and turbidity and temporarily increased sedimentation. In

[187] P. E. Raymond and H. C. Stetson: *A new factor in the transportation and distribution of marine sediments*, Science, n. s., vol. 73 (1931) p. 105-106.

[188] F. S. Russell and C. M. Yonge: *The seas* (1928) p. 243-250.

short, the Belt seas [139] of the Glacier Park facies were subjected to the most effective factors causing fluctuation of plant life in modern seas of equivalent latitude.

Many laminae probably were produced by fixed algae. Black [140] has described carbon laminae produced *in situ* by thin sheets or mats of algae which grow upon the sea floor during seasons of minimal sedimentation. Excess of sediment kills the algae, covers them with a drewite lamina, and the sequence is repeated. Altyn and Appekunny rhythms may be of this type; except for greater regularity and flatness, their carbon laminae resemble those figured by Black.

Other carbon laminae may have been produced by settling plankton, which should have found conditions in the shallow Belt seas periodically favorable to growth. Both sessile benthos and scavenging organisms were few, so that there was little to prevent the accumulation of carbonaceous laminae after periods of organic abundance.

The writers conclude, therefore, that rhythmic carbonaceous laminae in the Altyn were produced by seasonal fluctuations in plant life, each pair of laminae representing a year. Lack of such laminae chiefly characterizes sandy, pebbly, or argillaceous beds, commonly with mud breccias, and probably indicates removal of organic matter rather than failure of plant growth. Carbonaceous laminae in the Appekunny also may be assigned seasonal significance.

Carbon accumulated rhythmically in the Siyeh and Sheppard epochs, though throughout much of their duration it gathered in such abundance that the resulting rocks are almost black. This indicates the prevalence of conditions favorable to plant growth; lack of contrast between laminae suggests less drastic changes than those of the Altyn epoch. Aridity of adjoining lands may have diminished, with corresponding reduction in torrential floods and their destructive variations in salinity, turbidity and temperature. There is no evidence of effective deepening of seas; the presence of ripple marks, intraformational breccias, biostromes, and bioherms (reefs) negates it.

On this seasonal basis, rates of sedimentation may be estimated. Some carbonaceous laminae in the Altyn show 4 pairs (varves) to the centimeter; many show 7 or 8; a few 10 to 14. Thus, one has a time value of 4 to 14 years per cm.—10 to 35 years per inch. Carbon-bearing laminae in the Appekunny give rates of 6 to 18 years per cm., or 15 to

[139] Marine origin for the thick limestone-dolomite formations of the Altyn and Wallace is accepted even by Joseph Barrell [*Relative geological importance of continental, littoral and marine sedimentation*, Jour. Geol., vol. 14 (1906) p. 451, 560].

[140] Maurice Black: *The algal sediments of Andros Island, Bahamas*, Royal Soc. London, Philos. Tr., ser. B, vol. 22 (1933) p. 171.

45 years per inch. Dark and light laminae in *Collenia columnaris* Fenton and Fenton and *C. albertensis* n. sp. resemble those in enclosing strata; they number 4 to 16 pairs per cm. with an average of 10. The writers have not correlated the varves with algal laminae, for there is virtually no sediment between colonies in the Altyn biostrome, but the resemblance of organic and inorganic laminae suggests seasonal rhythms in plant growth.

Lime-Dolomite Rhythms.—Rhythmic alternations of gray limestone and dolomite, the latter bearing iron which seems to be the ferrous calcium carbonate isomorph of dolomite found by Steidtmann,[141] characterize some strata in the Altyn and a large part of the Siyeh and the Sheppard. Commonly, they involve layers, which contain 2 to 12 laminae, but, in some places, pairs of laminae show rhythms. In some strata, laminae seem to have originated through secondary segregation of dolomite and lime, but most of these rhythms seem to be primary or to have been produced by rhythmic replacement with dolomite soon after deposition. Both dolomites and limestone layers are mud-cracked, deformed, broken, and re-deposited in mud breccias.

Though these rhythms are associated with algae, they have not been correlated with fluctuations in algal growth. The fact that other inorganic and organic laminae coincide and are seasonal suggests that lime-dolomite rhythms, involving layers of 2 to 12 laminae, spread over periods of 1 to 6 years and were based upon fluctuations of material brought in solution to the Belt basin. No basis for such rhythms has been determined, nor for the fact that mud cracks affect dolomitic, rather than calcitic, laminae and layers.

Mudstone Rhythms.—Carbonaceous rhythms in Appekunny argillites of the Two Medicine region seem to be varves, the direct results of organic cycles. Most Appekunny rhythms, however, depend primarily on fluctuation in quantities of quartz and a green mineral, presumably chlorite. Pairs number 1 to 24 per centimeter, thus falling within the scope of seasonal laminae studied by Rubey.[142] More precise interpretation seems impossible.

Rhythms in red argillaceous sediments of the Grinnell, Spokane, and Miller Peak formations involve fluctuations in amounts of quartz, hematite, and chlorite, as well as breaks in which the only discernible change was diminution or cessation of deposition.

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[141] Edward Steidtmann: *Origin of dolomite as disclosed by stains and other methods*, Geol. Soc. Am., Bull., vol. 28 (1917) p. 431-450.

[142] W. W. Rubey: *Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region*, U. S. Geol. Surv., Prof. Pap. 165-A (1930) p. 1-54.

The significance of red color itself has been summarized by Twenhofel, following Blackwelder.[148] Red sediments indicate regions of good drainage, "good but not abundant" vegetation, and warm-temperate to tropical climate. If the sediments are deposited in the area of origin, there must be alternations of long dry and short moist seasons; if they are deposited elsewhere, that region must be free from plant accumulations sufficient to destroy red color.

All conditions except the "good" land vegetation are indicated by the Belt red beds, whose basin of deposition seems to have been at least periodically free from organic matter which might have reduced iron oxides brought to the sea. Flood deposits indicate precipitation adequate to oxidize iron compounds, though the process was retarded by quick run-off, as is indicated by the thin laminae in most red strata. Sandstones intercalated among red beds seem to be results of floods and segregation of grains by waves and currents.

Red beds in the Appekunny, Spokane, and Miller Peak differ from those of the Grinnell chiefly in more regular lamination and stratification, fewer strata of sand, and less evidence of bottom disturbance and floods. Mud cracks indicate fluctuations in water level; the Kintla and Mt. Rowe members of the Miller Peak contain abundant salt crystal casts. In general, sediments imply lands differing from those of the Grinnell only in reduced relief and in diminished contrast between dry and wet seasons.

Red mudstone rhythms in the Kintla member correlate with rhythms in the alga *Collenia clappii* n. sp. (Pl. 14, fig. 1), in which dolomite laminae, 0.2 to 2.5 mm. thick, alternate with argillaceous laminae, which range from faint pink bands to distinct layers, 0.1 to 0.6 mm. in thickness. The alga thus shows growth retarded by periodic accumulations of mud, alternating with more rapid growth and precipitation without this obstacle. This gives figures of 5 to 15 years per cm. for algal growth, and 10 to 30 years per cm. for argillaceous deposition. In beds above and below the *Collenia clappii* biostrome, rates range from 5 to 18 years per cm. The fact that strata contain no algae suggests that such rates exceeded the plants' tolerance of mud.

Collenia undosa Walcott, of the Spokane, contains mud-carbonate rhythms numbering 12 to 24 pairs per cm. The limy laminae are 0.2 to 0.7 mm. thick, the majority approximating 0.4 mm.; argillites commonly are films measuring 0.05 mm. or less, but some reach 3.5 mm. in thickness. They show irregular rhythms in thickness, involving 120 to 200 pairs of thin laminae and terminating in series of mud laminae 2.5 to 3 mm. thick.

[148] W. H. Twenhofel: *Treatise on sedimentation*, 2d ed. (1932) p. 774, 777, 779-781.

Evidently, there were long-ranging fluctuations in rates of clastic deposition which at their maxima smothered many algal colonies. Many, however, overcame the obstacle; some large colonies show three to five major interruptions.

As with *Collenia clappii* n. sp. of the Kintla, argillaceous layers within *C. undosa* are slightly thinner than those of the matrix, as if part of the mud was carried away. Absence of carbonate from that matrix, however, makes each pair of laminae within it considerably thinner than the corresponding pair within the fossils. Estimates range from 12 to 24 years per cm. for the fossils and from 16 to 28 years per cm. for the matrix. Intervening unfossiliferous beds show more rapid accumulation.

Though these rates are much lower than those generally assumed for mudstones, certain factors increase their probability:

Paucity of lime in Spokane sediments indicates that a small amount of it was available in the waters of that epoch. The growth of calcareous algal colonies was correspondingly reduced, so that the contrast between 4 to 16 years per cm. for Altyn specimens and 12 to 24 years for those of the Spokane becomes proper. Growth would be further reduced by the smothering effect of mud deposits.

Stratigraphically, 300 feet or less of Spokane in northern Glacier Park corresponds to 800 feet farther southward, to 3600 feet in Blackfoot Canyon, and to 7400 feet on Prickly Pear Creek (Fig. 2). Intergradation with the Sheppard above and the Siyeh below shows that disconformities are not present; there is no indication of disastems of great scope. It seems evident that the 300 feet represents the period of time required for the formation of thicknesses 12 to 25 times as great in other regions. The contrast may be attributed to three factors:

(1) Lack of coarse beds (sandstones, arkoses) present in southerly facies of the Spokane.

(2) Slow accumulation caused by paucity of sediment, determined by distance from a southern or southwestern source of clastic material.

(3) Minor diastems.

Factor 1 is of minor importance, for sandstones and arkoses nowhere form major parts of the Spokane. Factor 2 is emphasized by the fact that some apparent laminae seem to be layers composed of laminae too thin to be distinct or measurable. They suggest that over periods of years or perhaps even decades, sedimentation was so slow that the total accumulations form a unit with only the slightest indication of divisions.

Such situations grade into Factor 3. It may be impossible to distinguish layers that gathered at the rate of 1 mm. in 20 to 50 years from others between which sedimentation ceased for equal periods. As indicated by algal growth, planes between even "normal" argillaceous laminae are

seasonal diastems; broad areas of mud cracks extending through several laminae indicate greater intervals of non-sedimentation or erosion. For the Spokane of northern Glacier Park, an average rate of 65 years per inch is too high, for it allows only 234,000 years for accumulation of the 3600 feet of sediment in Blackfoot Canyon, or 7400 feet on Prickly Pear Creek. The Spokane of the Glacier Park facies illustrates the epochs of minimal sedimentation stressed by Barrell,[144] as does the Sheppard, which is 585 feet thick in Starvation Canyon and 6100 feet in Blackfoot Canyon.

Sand-Mud Rhythms.—Alternations or argillite and sandstone or quartzite characterize the Scenic Point, Rising Wolf, and Rising Bull members, though they are found throughout the Grinnell in its coarser phases, in the Collenia symmetrica zone, and in the basal Sheppard.

The argillites range from greenish brown to red, in thicknesses from 0.5 to 36 inches. They are finely to coarsely laminated, the laminae being warped in thin strata but horizontal in thick ones; planes between them commonly bear scattered sand grains and sandy lenticles 1 to 3 mm. thick. Many layers consist of flat-pebble mud breccias in which the matrix is little coarser than the pebbles. Mud cracks commonly are abundant; polygons range from flat to convex.

At the other extreme stand white to greenish quartzites in beds 1 to 20 inches thick. Most of them are cross-laminated and contain bent mud pebbles; some (Pl. 4, fig. 1) contain mud balls. In many places, cross-laminae of sand are intercalated with much finer laminae of red argillite (Pl. 7, fig. 1).

Among these strata are beds of rose-red to pale-pink sandstones or quartzite whose field habit is that of heavily bedded argillite. They bear wave and current ripple marks and mud cracks, contain horizontal or cross-laminae, and include many layers of mud breccia. Such rocks largely replace argillites in the Red Gap member of the Grinnell in the region of Gunsight Pass and in the Livingston Range. Their color is due to mud particles.

Despite these argillaceous sandrocks, there is little gradation between argillites and quartzites. They intercalate or interfinger; argillitic laminae extend into cross-laminated quartzites, but the boundary between them remains sharp (Pl. 7, fig. 1). With minor exceptions, the thickest and clearest quartzites are interbedded with thick argillites; the thin ones, with thin argillites or argillites that grade into red quartzites.

Within the major beds of alternating mudstones and sandstones, similar smaller rhythms are found. Layers or laminae are discontinuous and

[144] Joseph Barrell: *Rhythms and the measurements of geologic time*, Geol. Soc. Am., Bull., vol. 28 (1917) p. 786.

complicated by cross-lamination; thicknesses range from 5 to 100 mm. or more. Thus, they are on a scale commensurate with seasonal fluctuation. Each argillaceous layer suggests a dry season with red mud accumulation, generally ending in emergence, with formation of mud cracks, rain and hail prints, and salt crystals. This was followed by a season of flooding, with accumulation of sand and disturbances forming mud breccias. Where white sand layers are lenticular, it appears that the mud was broken into such fine particles that much of it was carried away, forming layers of mud farther from the center of disturbance.

Many mud-sand rhythms include strata too thick for seasonal accumulation. They indicate periods of flood, with accumulation of sand and disturbance of bottoms to depths involving the deposits of several years. Details of disturbance have been dealt with in connection with intraformational or mud breccias.

MARINE ORIGIN OF THE BELT

CRITERIA OF ORIGIN

To explain the lack of marine fossils, Walcott [145] suggested that Belt sediments accumulated in lacustrine basins. Mrs. Walcott [146] reports that he abandoned the hypothesis because of the great thicknesses of limestone and dolomite in northern Montana, and because of abundant salt crystal casts in clastic beds. Such a hypothesis is negated also by the presence of brachiopods in Newland limestones and shales.

Barrell [147] accepted the limestones and dolomites as marine, excluding the Sheppard because of Willis' statement that it was a quartzite.[148] He suggested that the other formations of the Glacier Park facies might indicate "subaerial origin by river aggradation." Daly [149] accepted this opinion for the Kintla and "possibly a limited thickness of Grinnell and Appekunny beds." Schofield [150] classed the entire Gateway of the Purcell facies as continental, with the Siyeh and the Kitchener as mainly continental, though with some "possibly marine" deposits. In the Phillipsburg region, Calkins [151] regarded the Spokane as of flood-plain origin but assigned the Prichard, Neihart, Ravalli, and Newland to marine or

[145] C. D. Walcott: *Abrupt appearance of the Cambrian fauna on the North American continent*, Smithson. Misc. Coll., vol. 57 (1910) p. 1-16.

[146] Mrs. C. D. Walcott: *personal communication.*

[147] Joseph Barrell: *Relative geological importance of continental, littoral, and marine sedimentation*, Jour. Geol., vol. 14 (1906) p. 451, 560.

[148] Bailey Willis: *Stratigraphy and structure, Lewis and Livingston ranges, Montana*, Geol. Soc. Am., Bull., vol. 13 (1902) p. 316, 324.

[149] R. A. Daly: *Geology of the American Cordillera at the forty-ninth parallel*, Geol. Surv. Canada, Mem. 38 (1912?) p. 83.

[150] S. J. Schofield: *Geology of Cranbrook map-area, British Columbia*, Geol. Surv. Canada, Mem. 76 (1915) p. 22-23.

[151] F. C. Calkins *in* W. H. Emmons and F. C. Calkins: *Geology and ore deposits of the Phillipsburg quadrangle, Montana*, U. S. Geol. Surv., Prof. Pap. 78 (1913) p. 34.

estuarine sedimentation. Schuchert and Dunbar[152] conclude that much shale in "eastern" sections of the Belt was deposited under marine conditions, but that several thick formations of red argillite and siltstone, bearing abundant mud cracks, accumulated on low surfaces above sea level. Much of the Appekunny, Grinnell, Spokane, and Missoula meets these specifications; no reason is given for exclusion of comparable green members.

There is, therefore, conflict of opinion among those who consider the Belt, or parts of it, to be non-marine. On Barrell's own criteria (clastics, abundant mud cracks), such formations as the Siyeh and Sheppard are marine in some facies and fluvial in others, and tongues of fluvial sediment extend, without unconformity or apparent disturbance, into marine se-

TABLE 1.—*Comparison of the Rising Bull, Kintla, and Medina*

Grinnell (Rising Bull)	Kintla	Medina
Red	Red	Red
Areal variations pronounced	Areal variations moderate	Areal variations moderate
Sand, muddy sand, mud	Muddy sand, mud	Sandy, muddy sand, mud
Cross-lamination abundant	Cross laminations restricted	Cross lamination common
Fine to coarse stratification, rhythmic	Fine stratification, rhythmic	Fine to coarse stratification, rhythmic
Wave and current ripples	Wave ripples	Wave and rare current ripples
Mud breccias, mud balls	.....	Mud breccias, mud balls
Current channels common	Current channels uncommon	Current channels abundant
Shore marks rare	Shore marks rare	Shore marks common
Abundant mud cracks	Few mud cracks	Cracks abundant in some strata
Salt crystals rare	Salt crystals abundant	.....
Rain and hail prints abundant in some layers	Rain and hail prints few	Rain and hail prints in some layers
Subaqueous lavas	Subaqueous lavas	.....
Annelid burrows a few feet above, in sand stone of basal Siyeh	Annelid burrows	Annelid burrows
.....	.....	Littoral brachiopods (*Lingula*)

quences. By limiting continental origin to sediments of red color, Schuchert and Dunbar introduce even greater complexity into the regularly bedded and minutely laminated Appekunny and Spokane.

To present the merits of conflicting hypotheses, two tables have been prepared. Table 1 compares the supposedly fluvial Rising Bull and Kintla with the definitely marine or estuarine Medina. The last may be distinguished only on paleontologic grounds and by scarcity of salt crystals. If physical characters are diagnostic, the Medina is fluvial.[153]

[152] Charles Schuchert and C. O. Dunbar: *A textbook of geology*, pt. 2, 3d ed. (1933) p. 88.

[153] Or deltaic, for Barrell's stated criteria seem to class the Belt clastics as deltaic rather than fluvial. [Joseph Barrell: *Relative geological importance of continental, littoral, and marine sedimentation*, Jour. Geol., vol. 14 (1906) p. 441-443.]

If they are not (and even littoral brachiopods do not inhabit flood plains), the Belt clastics may be marine.

Table 2 compares non-clastic formations. It shows that definitely marine formations display bottom disturbance, ripple marks, mud cracks, current channels, and areal variation associated with supposedly fluvial sedimentation. It also shows that, except in scarcity of marine organisms, the Goathaunt is more "typically" marine than either the Cedar Valley or the Southgate. Table 1 shows that Belt clastics may be marine; Table 2 indicates that the Goathaunt (typical Siyeh) and the Sheppard are marine. Close resemblances in the Altyn justify extension of the conclusion to that formation as well.

TABLE 2.—*Comparison of the Siyeh, Cedar Valley, and Southgate formations*

Siyeh (Goathaunt)	Cedar Valley (Bloody Run)	Cincinnatian (Southgate)
Gray	Buff	Gray
Dolomite and limestone	Limestone	Limy shale and mud breccia
Areal variations slight	Areal variations great, in short distances	.....
Disturbed bottoms—periodic	Undisturbed bottoms	Disturbed bottoms
Wave ripple marks	Wave ripple marks	Current ripple marks
Mud cracks imperfect	Mud cracks well developed	.....
Mud balls few	.....	Mud balls abundant
.....	Deep current channels	Small current channels
Salt crystals	.....	.....
Algal colonies and biostromes; individual colonies slightly eroded	Stromatoporoid biostromes, individual colonies much eroded, broken	Larger fossils (bryozoans) commonly eroded; no biostromes
Annelid and pelecypod burrows	Annelid burrows	Annelid burrows
Brachiopods in equivalent New-land	Brachiopods, mollusks, stromatoporoids (scanty fauna)	Abundant marine fauna

Marine origin of non-clastics is important in interpretation of clastic formations. As preceding discussions and Figure 2 show, limestones and dolomites of the easterly facies grade into clastics in the Purcell, Galton, and Cœur d'Alene facies. Even within the Glacier Park facies, there is gradation from carbonates in eastern exposures to clastics in western exposures, with no traces of shore lines or intervening uplift. Such areal variations imply a western source of sediments, not changes from sea basin to land.

All formations in the Glacier Park facies are joined by transition members, as are many in other facies. Each transition member indicates shallowing and occasional emergence, with action of waves and currents, increased salinity of muds, and crystallization of salt.

Though these saline members meet the physical requirements of continental deposition, five (upper Carthew member, Collenia symmetrica

zone, Granite Park member, basal Sheppard, uppermost Sheppard) include substantial sequences of dolomite or limestone; two (C. symmetrica zone, basal Sheppard) contain apparently marine fossils. They are neither followed nor preceded by disconformities; four transition zones (upper Carthew, Scenic Point, Granite Park, uppermost Sheppard) lead to clastic formations which show fewer traces of shallowing and exposure to air than do the transitional members. If, after the marine Altyn epoch, the Belt basin was uplifted to become land throughout the Appekunny and Grinnell epochs, it seems improbable that the transition took place without visible break, and that uplift was followed by depression and deepened water during the period of supposed emergence.

In short, the Belt series is unified areally and vertically. Several of its formations are admittedly marine; others differ from known marine formations only in scarcity of fossils and in special features which seem related to narrowness and climate of the Belt basin. With minor reservations to be noticed, the series appears to be marine.

BELT PALEOGEOGRAPHY

The Belt sea was long and narrow; through most of, if not all, its history, it was much shallower than any existing sea. Even in the Altyn and Siyeh-Newland epochs, it was so shallow that the bottom was affected by small waves, and had occasional periods of local emergence and drying.[154]

Such a sea presented several significant peculiarities. First, it was directly responsive to variation in precipitation on adjoining lands. Too shallow for tides and too much isolated for effective flooding from the Arctic or the Pacific, it presented a proportionately enormous surface for evaporation. Periods of drought, such as are indicated by textures and colors of sediments, resulted in lowering of water level, increase in salinity, and emergence of extensive areas of mud or sand. Succeeding periods of rainfall flooded the basin, inundating exposed areas, disturbing the semiconsolidated sediments, and producing channels, mud balls, mud breccias, and kindred structures. Even bottoms not exposed lay beneath such shallow water as to be easily affected, and small colonial algae growing upon exposed mud banks were rolled about.[155]

There is no evidence of great uplift or depression of the basin. Its eastern boundaries are largely hypothetical; westward, it reached into

[154] Shallows comparable to those of the Belt sea in Altyn, Siyeh, and Sheppard epochs characterized many epicontinental seas. Decorah, Cincinnatian, Waldron, Hamilton, Hackberry and similar Paleozoic faunas apparently dwelt in depths comparable to the modern littoral zone. The intertidal is rarely traced; substantial tides probably did not affect narrow epicontinental seas.

[155] The holotype of *Collenia undosa* Walcott shows such rolling, as do many other specimens of that species which characteristically grew on mud-cracked surfaces. [*See* C. D. Walcott: *Pre-Cambrian Algonkian algal flora*, Smithson. Misc. Coll., vol. 64 (1914) pl. 13.]

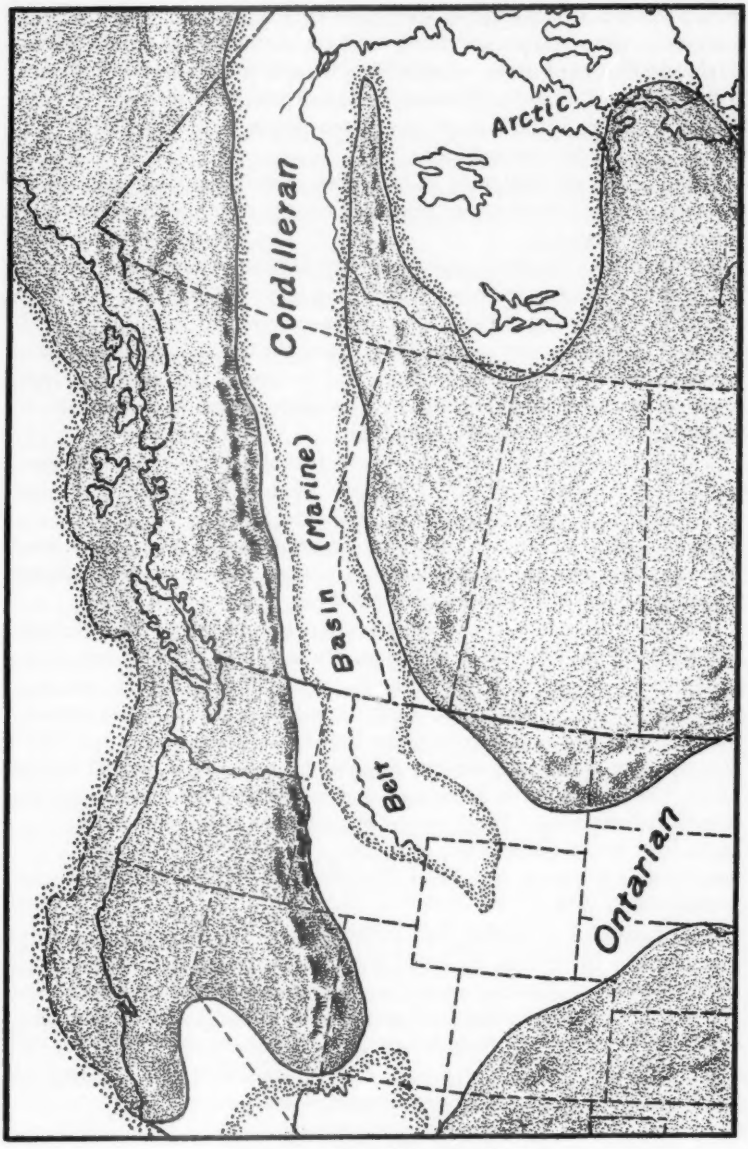

FIGURE 13.—*Belt Paleogeography*

Lands, dark; geosynclines, white; marine basins, stippled at borders. Modified after Cooke.

British Columbia, Washington, and Idaho (Fig. 13). Within these bounds, it seems to have maintained fairly uniform depth except during Altyn, Siyeh, and Sheppard times, when relatively rapid accumulation of clastics to the westward caused shallowing in that direction. Clastics may have built temporary, littoral flood plains, too nearly continuous with submarine deposits for recognition.

Though vertical coarsening of sediments may be attributed to uplift of lands, several facts argue against contemporary uplift of the Belt sedimentary basin:

(1) Transition members are essentially uniform throughout the Belt, yet they are found at the base and the top of each formation, regardless of the ensuing change. Thus, identical members lead from green mudstones of the Appekunny to red mudstones of the Grinnell, and from these to the dolomites of the Siyeh. The same is true of the transition from Siyeh to Spokane (dolomite to green mudstone) and from Spokane to Sheppard (green mudstone to dolomite).

(2) All transition members indicate increased activity of shoal waters, rather than emergence of earlier shoals. Mud cracks generally are less abundant than in argillaceous non-transitional members.

(3) Actual evidence of emergence (imprints, salt-crystal casts, mud cracks) is no more abundant than is consistent with shallowing through temporary increase in rate of sedimentation.

It appears, therefore, that each epoch was terminated by land changes, which resulted in increase of sediment. In some cases this change seems to have been general uplift, resulting in accumulation of clastics and consequent silting-up of the basin. In the Appekunny, it resulted in coarsening of clastics and change from green to red. In two instances it resulted in temporary increase in clastics followed by diminution and, in several facies, the deposition of limestones and dolomites of the Siyeh and the Sheppard formations. These epochs of carbonate sedimentation were accompanied by long-continued but slow depression of the basin, as evidenced by reduction in abundance of ripple marks, desiccation mud cracks, and imprints.

The lands that furnished Belt sediments seem to have been higher in southwestern Idaho than in Washington, for they provided much greater quantities of both dissolved and suspended sediment during several epochs. If mountainous, they were not so immediately adjacent to the basin, though arid areas, from which arkosic materials of the Altyn and the Goathaunt were carried, may have had substantial relief. Reasons for assigning wet and dry seasons to them have been given.

PART III. PALEONTOLOGY

FOSSILS

CALCAREOUS ALGAE

In describing and naming species of supposed calcareous algae, the writers do not imply that these groups constitute actual biologic species. From comparison with modern algal deposits whose origins are known,[156] it seems probable that several different algae were involved in the production of each paleontologic form-species. It is assumed, however, that these commensal groups were constant: that those producing *Collenia frequens* Walcott, for instance, normally built it and not *C. willisii* or *C. undosa* Walcott. Reasons for this assumption are:

(1) Form-species of algae are so widespread at given horizons that they serve as index fossils.

(2) Despite known ecologic variations in colonial size and shape, they retain recognizable structures, as do some modern polyspecific "matrices."

(3) Some form-species, such as *C. undosa* Walcott, are limited to a single type of habitat and do not occur among others, even in modified form. Some modern species-groups show comparable limitation.

(4) At least one form-species—*C. willisii* n. sp.—maintains stable characters of shape and laminae in habitats ranging from precipitated, carbonaceous lime flats to mud-breccia deposits and flats of siliceous mud. Such stability implies a stable group of commensal species.

No opinion is expressed as to relationships of these form-species with either the blue-green (Cyanophyceae) or red (Rhodophyceae) algae. The problem of relationship is important, but it does not affect correlations of algal horizons in the Glacier Park facies with those of other facies and regions. Algae of the Meagher facies have been considered in another paper.[157]

Collenia columnaris Fenton and Fenton

(Plate 9, figures 1, 2)

Collenia columnaris Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 682, plas. 1-2.

DESCRIPTION: Colonies large, elongate-columnar, standing at angles of 40° to 85° to the bedding planes. Laminae thin, forming elongate-oval convex layers which describe arcs of 30° to 160°, and are only approximately concentric. Growth in biostromes generally is compact, with little or no space between columns; in a few places (Pl. 9, fig. 2), colonies are isolated, interstices being filled by sediment. Colonies isolated in massive dolomites are much smaller than those of biostromes. Typical sizes are indicated by Figure 14.

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[156] Maurice Black: *The algal sediments of Andros Island, Bahamas,* Royal Soc. London, Philos. Tr., ser. B, vol. 22 (1933) p. 165-192. Algal masses of Black's Type B closely resemble those described in this section as well as many supposed algae of Paleozoic age.

[157] C. L. Fenton and M. A. Fenton: *Walcott's "Pre-Cambrian Algonkian algal flora" and associated animals,* Geol. Soc. Am., Bull., vol. 47 (1936) p. 609-616.

REMARKS: In its columnar growth, this species resembles *Collenia kona* Twenhofel[188] of the Lower Huronian, but appears to form more distinct colonies, with less uniform direction of growth and more irregular laminae.

OCCURRENCE: Upper part of the Hell Roaring member of the Altyn. Specially

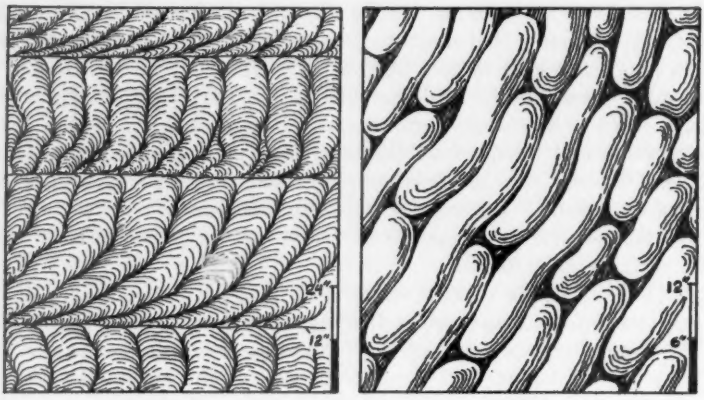

FIGURE 14.—*Collenia columnaris Fenton and Fenton*

(A) Natural section of biostrome, showing varied inclinations of colonies in successive strata. (B) Surface of the biostrome, showing colonies 32 inches in length.

abundant along the front of Mt. Appekunny, near Appekunny Falls, Glacier National Park.

Collenia albertensis n. sp.

(Plate 11, figure 2)

DESCRIPTION: Colonies irregularly columnar, oval in transverse section. They are expanded basally, then constricted, and expanded again. Laminae thin, approximately concentric, convex to flattened. Growth solitary, though not invariably with such wide separation as is shown in Figure 15.

REMARKS: Ranging northward from Gable Mountain, this species commonly is associated with mud breccias, cross-lamination, and other evidence of disturbed waters. It may be an ecologic form of *Collenia columnaris* Fenton and Fenton, but intermediates have not been found.

OCCURRENCE: Hell Roaring member of the Altyn: Gable and Bertha mountains, west foot of Vimy Peak, and ledges near Cameron Bend, Waterton-Glacier parks.

Collenia symmetrica Fenton and Fenton

(Plate 10, figure 2; Plate 13, figure 2)

Collenia symmetrica Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 683, pls. 3-5.

DESCRIPTION: Colonies depressed-spheroidal to irregularly concavo-convex; subcircular in outline. Laminae thin, highly carbonaceous, flattened centrally but

[188] W. H. Twenhofel: *Pre-Cambrian and Carboniferous algal deposits*, Am. Jour. Sci., 4th ser., vol. 48 (1919) p. 346.

abruptly convex marginally, where they are compressed. In many solitary specimens the edges of the laminae are elevated and then abruptly depressed.

REMARKS: A unique peculiarity of this species is the abundance of fossils in which all or part of the laminae have disappeared, leaving a mass of dark-gray dolomite,

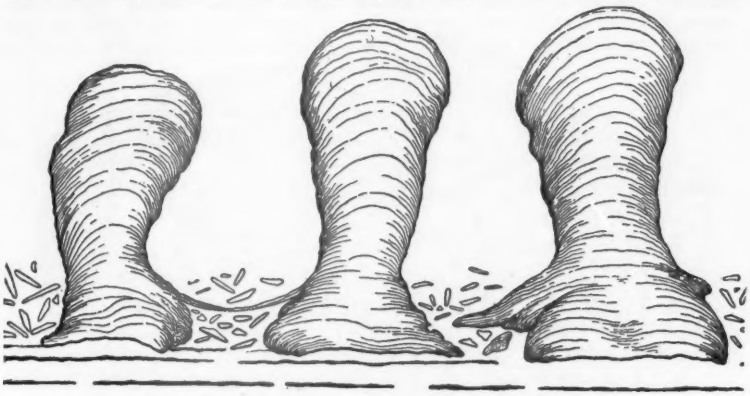

FIGURE 15.—*Three colonies of Collenia albertensis n. sp.*

Note partial smothering by deposit of edgewise mud breccia (lime-dolomite) and subsequent secondary expansion. Hell Roaring member of the Altyn formation, lake shore trail south of Waterton Park. × 0.5.

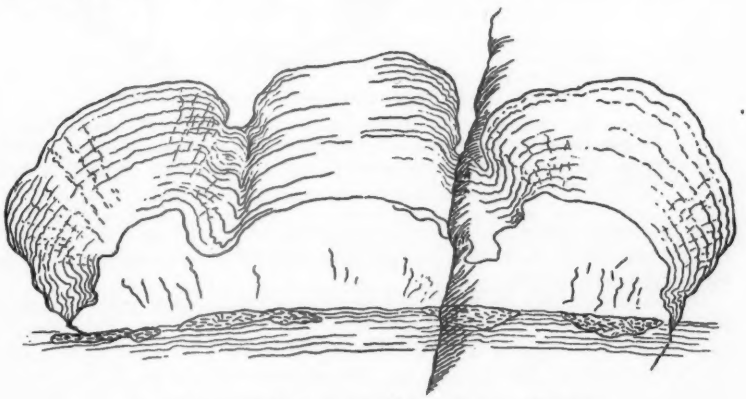

FIGURE 16.—*Collenia symmetrica Fenton and Fenton*

Compound colony, showing marginal down-curvature of laminae and basal zone in which laminae are not disinguishable; Collenia symmetrica zone, talus near Sexton Glacier. Greatly reduced.

which may show traces of "molar tooth" structure. Such a colony is shown in figure 2 of Plate 10; in Figure 16, only the lower portion lacks laminae. Such colonies are especially common on Dawson Pass, where there also are abundant, well-preserved fossils.

Still more complex is the specimen of Figure 17. It shows two basal, irregular masses (A, B) of dark-gray dolomite without laminae, crossed by *Drucksuturen* and vertical or flexuous solution lines which do not form styolites. Between them is a partial filling (C) of edgewise breccia; above this a fine-grained edgewise filling (D), which is replaced laterally by convex laminae. On the right, these

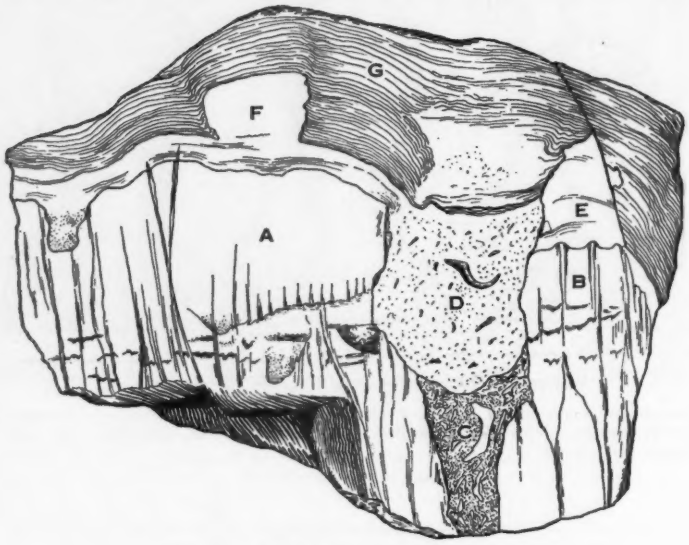

FIGURE 17.—*Collenia symmetrica Fenton and Fenton*

Showing loss of laminae. (A, B) Dolomite without laminae. (C) Edgewise breccia. (D) Fine-grained edgewise breccia. (E) Irregularly laminated column. (F) Low laminated column. (G) Algal laminae. Collenia symmetrica zone, Dawson Pass. × 0.5. (Princeton University Collection.)

form an irregular column (E); the other is surmounted by a low column (F), which enlarges upward and is bounded by apparently undisturbed algal laminae (G) containing abundant carbon.

That these structures are not typical stylolites is plain, though typical stylolites do extend into, and even through, colonies of *Collenia symmetrica*. They seem to have involved: (1) erosion (probably subaqueous) of the basal dolomite, with partial re-deposition of the same or very similar material in some of the crevices formed; (2) formation of algal deposits upon the projections; (3) deposition of fine edgewise breccia with sand grains, which partly killed the algal colonies; (4) revival of algal growth, producing the tops of E and F—colonies with readily diagenized layers; (5) cessation of algal growth; and (6) growth of a new colony, surrounding and covering the old ones and projecting sediments on which they rested. Much later came the development of *Drucksuturen* and comparable vertical seams. Contacts suggest that diagenesis and destruction of laminae came at two periods—between (2) and (3) and during (5).

OCCURRENCE: Basal Siyeh (*Collenia symmetrica* zone), throughout Waterton-Glacier parks.

Collenia willisii n. sp.

(Plate 10, figures 1, 3; Plate 11, figure 1; Plate 12, figures 4-6; Plate 13, figure 1)

Collenia sp. Fenton and Fenton, Jour. Geol., vol. 39 (1931) pl. 10.

DESCRIPTION: Colonies large, convex or flattened, irregularly discoid. Laminae characteristically are depressed-convex, with irregularly disposed, rounded mammillae, 10 to 20 millimeters in diameter which show clearly on the upper surfaces

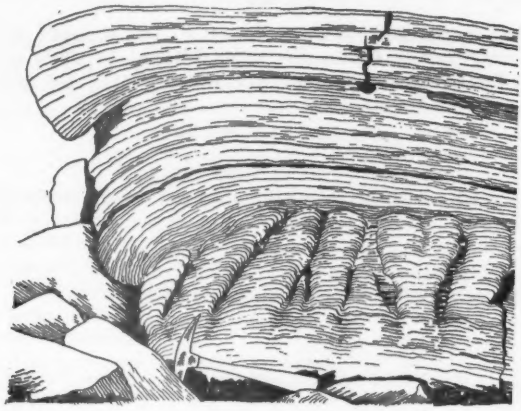

FIGURE 18.—*Collenia willisii n. sp.*

Natural section through a compound colony whose medial portion is divided into irregualr columns which unite in a flattened, discoid mass. Siyeh (Goathaunt), near Alderson Lake, Waterton Lakes National Park.

of the colonies. In some colonies, however, these mammillae are so closely spaced that the laminae assume a crenulate appearance, this being most common in the growth-form prevalent in the Goathaunt member at and near Indian Pass.

In early stages, colonies consist of small, expanding columns like that illustrated in Figure 6 of Plate 12. If solitary, these expand into colonies like those shown in Figure 1 of Plate 10, Figure 1 of Plate 11, and Figure 1 of Plate 13. Where they are crowded, many columns may unite into a single discoid mass with continuous, flattened laminae (Fig. 18) or form complex masses in which outlines of each colony are preserved (Pl. 10, fig. 3). Such union is most common in biostromes, where crowding is greatest, but maximal size is achieved in biostromes of moderate crowding. In them, colonies reach diameters of 8.5 feet and thicknesses of 3 to 4.5 feet. The largest seen are those illustrated by the writers as *Collenia* sp. in 1931.

Specimens collected near Liverpool Creek, Cooper's Lake quadrangle, Montana, lay in a matrix of green argillite, which forms laminae within the colonies. One specimen shows mammillae and a vertical section almost identical with those of Glacier Park specimens. The other is expanded and depressed and has major mammillae, 40 to 70 millimeters in diameter, on which smaller ones are developed. Basally, the laminae are only slightly crenulate; near the top, they resemble those of *Collenia undosa* Walcott. This suggests that *undosa* and *willisii* may be extremes in the development of a definite group of symbiotic algal species which

grew in both lime-mud and clay-mud habitats. Permanency of the apparent extremes, however, demands specific distinction.

OCCURRENCE: Siyeh: middle to upper Goathaunt and Granite Park members, especially at Indian and Logan passes and in Hole-in-the-Wall Basin, Glacier National Park. Newland, Cooper's Lake quadrangle, Montana.

Collenia frequens Walcott

(Plate 15, figures 1, 2)

Cryptozoan frequens Walcott, Geol. Soc. Am., Bull., vol. 17 (1906) pl. 11.
Collenia? frequens Walcott, Smithsonian Misc. Coll., vol. 64 (1914) p. 113, pl. 10, fig. 3; Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 685, pl. 8, fig. 1.

FIGURE 19.—*Ecads of Collenia frequens Walcott*

Collenia frequens Fenton and Fenton, Geol. Soc. Am., Bull., vol. 44 (1933) p. 1135-1142, fig. 2; pl. 57.
Collenia compacta Walcott, Smithsonian Misc. Coll., vol. 64 (1914) p. 112, pl. 15, fig. 7.

DESCRIPTION: Colonies typically elongate-conical; they generally stand with the long axes at angles from 50° to 70° to the bedding planes. Each colony consists of concentric, conical laminae, which number 8 to 15 in a thickness of 1 centimeter, and are grouped into layers 4 to 10 millimeters thick. Diameters range from 5 to 75 centimeters (2.5 feet), and heights attain 90 centimeters (3 feet). oblique sections resemble cone-in-cone, except that apices of laminae are rounded, and sides curved.

In biostromes, but especially in bioherms (Pl. 17), laminae of conical colonies are continuous with flexuous laminae which spread over other colonies and even over the bottom. This is the form called *C. compacta* by Walcott. In other places, conical colonies intermingle with irregular, concentric masses, best shown to the left of the middle bioherm on Plate 17. A fourth form shows at the base of the third bioherm on that plate: irregular, concavo-convex colonies resembling *Collenia symmetrica*, but with traces of conical lamination. Ecologic relationships of these forms, or ecads, are indicated by Figure 19.

REMARKS: Identification of this species as Walcott's *Cryptozoan frequens* is based on its great abundance, its habit of forming massive biostromes, and its prevalence in the Siyeh. Named without description, its types seem to be two photographs of a single slab, made in the field by Bailey Willis. They show a biostrome of erect, dome-shaped to subconical colonies which rest upon "molar tooth" Siyeh strata. Walcott's brief description of 1914 gives only range of dimensions and an approximate locality: Little Kootenai Creek (= Kootenai River). The photographed ledge seems to be in place, and it probably lies near the head of the river.

Should it prove that this species is not Walcott's *C. frequens*, the name *compacta*, here considered a synonym, will apply.

OCCURRENCE: Siyeh: Collenia frequens zone and basal Granite Park member, Waterton-Glacier parks.

Collenia versiformis n. sp.

(Plate 14, figure 2; Plate 16, figure 4; Plate 18, figures 1, 2)

Collenia compacta Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 684, part.

DESCRIPTION: Colonies columnar, turbinate, or massively laminate. Typically, they begin as flexuous columns resembling those of *C. columnaris* Fenton and Fenton of the Altyn, though with more uniformly convex laminae and less regularity of growth. The holotype (Pl. 14, fig. 2) shows variations in thickness and curvature of laminae; pronounced constrictions are shown in Figure 1 of Plate 18. With further growth, colonies commonly expand, and from expansion fuse into the flattened or turbinate masses visible in Figure 2 of Plate 19, and in the writers' figure of 1931. In other strata, the colonies form subconical groups or unite in masses suggesting those of *C. willisii;* both are shown on Plate 17. In all, however, the column remains basic to later modification.

REMARKS: The tendency of this species to unite, or to form laminar expansions, is productive of confusion. On one hand, it closely resembles *C. frequens* Walcott as that species is here interpreted; on the other, it so closely resembles *C. willisii* n. sp. that only its lack of mammillae serves to distinguish it. Where only natural sections are available (as in the third or uppermost bioherm of Plate 17), identifications must be made from association, which there indicates *C. versiformis.*

To this species, the writers doubtfully refer the specimen shown in Figure 4 of Plate 16, and three others collected by Charles Deiss. They resemble *C. versiformis* of Glacier Park in its least columnar form; two specimens seem to be horizontally elongate. Laminae are regularly convex to flattened or even centrally depressed, as in the figured specimen.

OCCURRENCE: Siyeh: Uppermost Collenia frequens zone and Granite Park member, Glacier National Park. Perhaps in the Helena (= Spokane) of Rogers Pass and Ford Creek, Cooper's Lake quadrangle, Montana.

Collenia undosa Walcott

(Plate 11, figures 3-4; Plate 14, figure 3)

Collenia undosa Walcott, Smithsonian Misc. Coll., vol. 64 (1914) p. 113, pl. 13, figs. 1-2; pl. 14, figs. 1-2; Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 684, pl. 6, pl. 7, figs. 3-5.

DESCRIPTION: Colonies simple to compound. In early stages, they are concavo-convex or dome-shaped; with growth, they unite laterally with adjoining colonies

into thin expansions with domed or botryoidal upper surfaces. Laminae in such a colony are shown in Figure 4 of Plate 11; even the specimen illustrated in Figure 3 of Plate 11 is part of a compound colony. Sizes range from simple colonies, 0.5 inch or less in width, to compound expansions, 5 feet wide and 10 to 15 inches thick.

REMARKS: Ecologic relationships of this species have been discussed in connection with rhythms and marine environments. Figure 3 of Plate 14 shows it upon a sandy bottom; in most places, it adopted mud-cracked shale.

OCCURRENCE: Spokane formation, Waterton-Glacier parks. Specially abundant along the Garden Wall trail southeast of Granite Park, and near Logan Pass.

Collenia parva n. sp.

(Plate 14, figure 4)

DEFINITION: Individual colonies small, ranging from 12 to 17 millimeters in width and from 6 to 8 millimeters in height; concavo-convex to flabellate. Laminae thin. Colonies so compactly packed that few bedding planes can be distinguished; the interspaces, however, are filled with fine micaceous sand.

REMARKS: This species is characterized by its small size and thin laminae, both of which may have been determined by scarcity of dissolved lime. *Collenia parva* may be a diminutive forerunner of *C. clappii*, though the latter characteristically begins growth as expanded films several centimeters in width, not as the minute bodies indicated by flabellate specimens of *C. parva*.

OCCURRENCE: Siliceous beds of the Sheppard, in the Boulder Peak region, Glacier National Park.

Collenia clappii n. sp.

(Plate 14, figure 1)

DESCRIPTION: Colonies concavo-convex, typically broadly expanded, ranging from 5 centimeters in width and 7 in height in a slightly compressed colony to 105 centimeters in width and 30 centimeters in height. The holotype (apparently incomplete) measures 15 and 6 centimeters, respectively. Laminae fine, moderately arched centrally and subparallel. Marginally, the curvature is more abrupt but rarely results in overlapping.

REMARKS: Lamination is made conspicuous by apparently seasonal layers of red argillite which are discussed under rhythms in argillites.

OCCURRENCE: Lower Kintla, where it forms conspicuous bioherms in the regions of Boulder Peak and Akamina Pass, Waterton-Glacier parks.

Collenia expansa n. sp.

(Plate 16, figures 1-3)

DESCRIPTION: Colonies expanded, laminar or sheet-like. They consist of fine, flexuous laminae which number 20 to 46 in a thickness of 5 millimeters. They rise in gently to abruptly convex mammillae which, in the types, are 7 to 35 millimeters in diameter and 1 to 10 millimeters high. The largest mammillae are formed by fusion of several, which are distinct at lower levels. Furrows between mammillae are narrow and subangular. Vertical sections show indistinct, imbricating or vesicular columns, which are strongest in the mammillae. Both holotype and paratype contain limy oölite grains 0.5 to 1.5 millimeters in diameter. No inter-

gradation with colonies of convex or columnar form was noted by the collector, Charles Deiss.

OCCURRENCE: Limestone, probably equivalent to the Hellgate quartzite of the Missoula section. Ridge 2 miles northeast of Steamboat Mountain, north of the North Fork of Dearborn River, Lewis and Clark County, Montana.

Newlandia sarcinula Fenton and Fenton

Newlandia sarcinula Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 685, pl. 7, figs. 1-2.

DESCRIPTION: Colonies small, subspheroidal. They consist of regular, concentric laminae, which number 9 to 11 in 5 millimeters, connected by regular to irregular, radiating rods and partitions. The species differs from *N. lamellosa* Walcott,[159] its nearest relative, in being smaller, and in having finer laminae and more regular radiating partitions.

OCCURRENCE: Altyn (Hell Roaring) on Spot Mountain, Glacier National Park. Rare.

NON-CALCAREOUS ALGAE

As was pointed out in the discussion of carbon rhythms, many gray laminae in dolomites and green argillites probably are algal films. Algae also may have served as binders in the pebbles of Altyn and Siyeh mud breccias or on the surfaces of subaqueous mud-crack polygons. Only two non-calcareous algae, however, are identifiable as fossils.

Beltina cf. *danaii* Walcott

(Plate 2, figure 4)

Beltina danaii? Fenton and Fenton, Jour. Geol., vol. 39 (1931) p. 686.

REMARKS: Irregular carbonaceous fragments, some of which superficially resemble segments or appendages of merostomes. In beds subjected to deformation, they grade into irregular areas of carbon on bedding planes. They appear to be fragments of thallophytes, probably brown algae comparable in form to the modern *Scytosiphon.*[160]

OCCURRENCE: Hell Roaring member of the Altyn, chiefly above the Collenia columnaris zone. Abundant near Many Glaciers and in Cameron Valley, Waterton-Glacier parks.

Morania antiqua n. sp.

(Plate 2, figure 5)

DESCRIPTION: Colonies apparently coriaceous, globose, ovoid or discoid, attached or free-floating. In advanced stages, they broke and spread into irregular, flattened expansions which formed carbonaceous films less definite in outline than those of young colonies. Diameters of typical bodies range from 3 to 8 millimeters. Some specimens bear faint films suggesting a gelatinous base enclosing several colonies. Microstructure unknown.

[159] C. D. Walcott: *Pre-Cambrian Algonkian algal flora,* Smithson. Misc. Coll., vol. 64 (1914) p. 106.

[160] J. E. Tilden: *The algae and their life relations* (1935) p. 251.

REMARKS: Specimens of this species closely resemble small colonies of *Morania confluens*, Walcott,[161] the genotype. They are associated with the less regular, apparently segmented fossils referred to *Beltina*.

OCCURRENCE: Hell Roaring member of the Altyn, above the Collenia columnaris zone, Waterton-Glacier parks. Common in cliffs near Roes Creek, Glacier National Park.

TRAILS AND BURROWS

Figure 2 of Plate 19, shows filled, non-annulate burrows in coarse, brown quartzite of the Collenia symmetrica zone, near Dawson Pass. Lighter-colored beds, of approximately equivalent age, on the trail from Baring Basin to Sexton Glacier, afforded specimens of essentially similar type. One fragment contains portions of three burrows, 5.5 to 9 millimeters in width, the largest showing a branch 13 millimeters long and 3.5 millimeters wide. The annelids which made them followed a bedding plane between gray mud and nearly white sand, the burrow contours being discernible in both, though fillings are of sand.

Dolomites of the Collenia symmetrica zone on Dawson Pass afforded the traces illustrated in Figure 1 of Plate 19. They consist of channels, 7 to 8 millimeters wide, which terminate in subovate depressions, measuring 8 by 17 millimeters and 9 by 16.5 millimeters. The traces are partly filled with gray, shaly stone, distinct from the buff-weathering dolomite in which they are sunk.

Annelids or other worm-like animals do not make marks of this type. Snails make trails ending (or beginning) in subovate impressions, but they are either very shallow and transversely ridged, as in *Climactichnites*,[162] or flat with bounding ridges, as in the Cambrian trails and those of *Littorina*[163] and *Ilyanassa*.[164] More closely comparable are the traces made by pelecypods, which first crawl and then burrow or partly bury themselves in mud. In so doing, they may dig angular trails; in many examples, that angularity is destroyed by movements from side to side, by the expansion of a large, blunt foot, or by slumping of soft muds and muddy sands. When a pelecypod begins to burrow, it commonly twists from side to side, digging an ovate basin and throwing a slight ridge across its trail. Some pelecypods burrow so rapidly that the sediment closes in without trace of their passage; others half float from their terminal depressions, leaving faint, readily obliterated trails. Still others lie quiet for some time, repeat their sidewise twisting, rise from the basins thus made, and crawl away.

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[161] C. D. Walcott: *Middle Cambrian algae*, Smithson. Misc. Coll., vol. 67 (1919) p. 226.

[162] L. D. Burling: *Protichnites and Climactichnites; a critical study of some Cambrian trails*, Am. Jour. Sci., 4th ser., vol. 44 (1917) p. 390-397.

[163] C. L. Fenton and M. A. Fenton: *Apparent gastropod trails in the Lower Cambrian*, Am. Midl. Nat., vol. 12 (1931) p. 401-405.

[164] C. L. Fenton and M. A. Fenton: *Arthraria-like markings made by annelids and snails*, Pan-Am. Geol., vol. 61 (1934) p. 264-266.

Lack of trails leading from the subovate depressions suggests that these Belt traces are termini rather than starting points, and that constriction of the trails near them is due to mud cast up by sidewise twisting preparatory to resting or burrowing. Such similarities justify

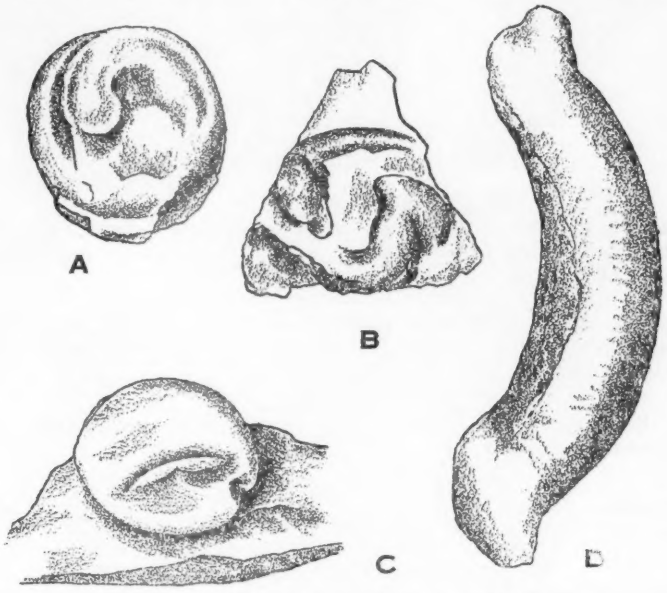

FIGURE 20.—*Problematic structures of Sheppard age* × 1. (Princeton University Collection.)

tentative interpretation of these traces as the work of Proterozoic pelecypods.

Figure 20 shows problematic structures from green-gray argillites of the basal Sheppard. *D* is the filling of a trail or burrow whose outer margin has been flattened during slipping. *A-C* show depressed, irregularly spiral cakes, whose partial coiling suggests annelid castings, though castings of such size and distinctness should be associated with vertical burrows, which are absent. Surface slickens suggest diastrophic origin, though the strata show no twisting.

Flexuous annelid burrows, too poorly preserved for photography, were found in the lower Kintla member, near Boulder Pass. Other flexuous markings are exposed on rippled slabs of Missoula age, near the Middle Fork of the Flathead River.

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PLATE 2. BELT SEDIMENTS AND ALGAE

FIGURE 1.—MUD BRECCIA

Goathaunt member of Siyeh near Alderson Lake, Waterton Lakes Park. Dark pebbles, chert; others, dolomitic limestone in dolomite matrix. ×0.5. (Princeton University.)

FIGURE 2.—CHANNEL FILLINGS

Grinnell (Rising Wolf?), Bighorn Basin, at the foot of Pumpelly Pillar, Glacier National Park. Channels seem to have been made by mud balls rolling on a shoal bottom. ×0.3.

FIGURE 3.—CASTS OF CUBICAL SALT CRYSTALS

In Kintla argillaceous quartzite. Boulder Pass, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 4.—BELTINA CF. DANAII WALCOTT

Fragment suggesting a mouth part of a crustacean, but apparently part of a brown alga. ×1. (Princeton University.)

FIGURE. 5.—MORANIA ANTIQUA N. SP.

Holotype, showing carbon films representing colonies of several sizes. Specimens of figures 4 and 5 are from Morania zone of the Altyn on the highway near Swiftcurrent Falls, Many Glaciers, Glacier National Park. ×1. (Princeton University.)

BELT SEDIMENTS AND ALGAE

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BELT SEDIMENTS

PLATE 3. BELT SEDIMENTS

FIGURE 1.—CHANNEL FILLINGS OF FINE-GRAINED QUARTZITE

Channels lie in dolomite and appear to have been caused by small waves breaking and running over a mud-cracked surface. From Sheppard, northern slope of Boulder Peak, Glacier National Park.

FIGURE 2.—EDGEWISE MUD BRECCIA

Dolomite pebbles in arenaceous matrix, overlying earthy dolomite. Northwest slope of Boulder Peak, Glacier National Park, below the beds shown in figure 1.

PLATE 4. MUD BALLS AND BRECCIAS

FIGURE 1.—MUD BRECCIA IN QUARTZITE MATRIX

Grinnell (Rising Wolf?), foot of Pumpelly Pillar, Glacier National Park. Both balls are bent, angular pebbles consist of deep-red argillite; the quartz sands enclosing them are slightly rounded. Much reduced.

FIGURE 2.—MUD BALL (STORM ROLLER)

Arenaceous, micaceous argillite in finely laminated argillite. Spokane, near Logan Pass, Glacier National Park.

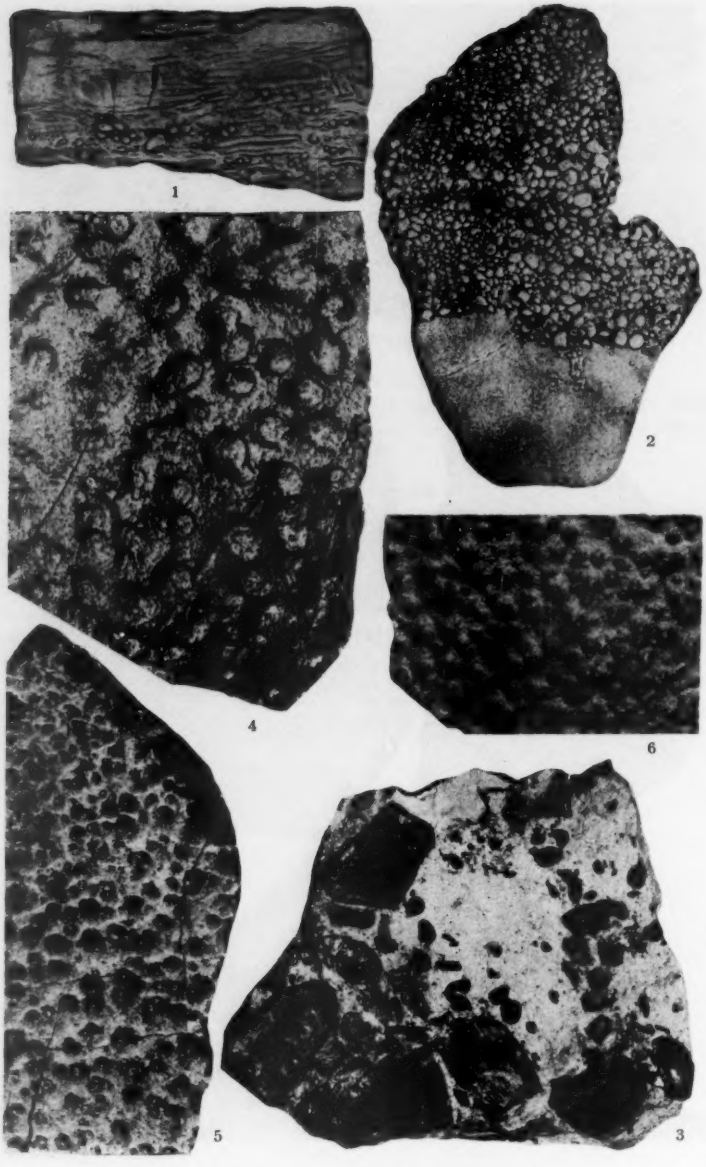
FIGURE 3.—EDGEWISE MUD BRECCIA

Most of the pebbles consist of cross-laminated dolomite in gray limestone matrix. Siyeh (Goathaunt), moraine of Sexton Glacier, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 4.—"MOLAR TOOTH" STRUCTURE, WITH TRACES OF MUD CRACKING

Light parts, dolomite; interstices, gray limestone. Siyeh (Goathaunt) drift boulder, Avalanche Valley, Glacier National Park. ×0.3. (Princeton University.)

MUD BALLS AND BRECCIAS



SEDIMENTARY STRUCTURES

PLATE 5. SEDIMENTARY STRUCTURES

FIGURE 1.—MUD BRECCIA CONTAINING SUBANGULAR SAND GRAINS

Altyn, Forty-mile Creek, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 2.—CONGLOMERATE AND SANDSTONE

Basal Appekunny (Singleshot), near Appekunny Falls, Swiftcurrent Valley, Glacier National Park. These beds contain fragmentary algae (text Figure 3). ×0.5. (Princeton University.)

FIGURE 3.—MUD BRECCIA IN QUARTZITE

Grinnell (Rising Wolf), north shore of Two Medicine Lake, Glacier National Park. The pebbles consist of red argillite; finely divided mud makes the quartzite pink. ×0.5. (Princeton University.)

FIGURE 4.—RAIN OR BUBBLE PRINTS

Appekunny (Upper Appistoki), Scenic Point trail above Two Medicine Valley, Glacier National Park. Obliquity of direction indicates that these are rain prints. ×1. (Princeton University.)

FIGURE 5.—SLEET PITS IN FINELY LAMINATED GREEN ARGILLITE

Appekunny (Upper Appistoki), Scenic Point trail, Glacier National Park. ×1. (Princeton University.)

FIGURE 6.—FILLINGS OF PITS

Like those shown in figure 5. ×1. (Princeton University.)

PLATE 6. SEDIMENTARY STRUCTURES

FIGURE 1.—MUD CRACKS AND CASTS OF SALT CRYSTALS IN PURPLISH, DOLOMITIC ARGILLITE Siyeh (Granite Park), moraine at Iceberg Lake, Glacier National Park. These beds are exposed above the trail on the northwestern slopes of Mt. Wilbur.

FIGURE 2.—LAMINAE AND MUD CRACKS IN GREEN ARGILLITE OF THE LOWER SPOKANE Moraine of Clements Glacier, near Logan Pass, Glacier National Park.

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SEDIMENTARY STRUCTURES

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SEDIMENTARY STRUCTURES

PLATE 7. SEDIMENTARY STRUCTURES

FIGURE 1.—CROSS-LAMINATION, INTERCALATION OF MUDS AND SANDS, MUD BALLS, AND BRECCIAS

Grinnell (Rising Wolf), Pumpelly Pillar, Glacier National Park. Structures interpreted as results of seasonal flooding.

FIGURE 2.—MUD CRACKS ENCLOSING CONVEX POLYGONS

Red beds of Appekunny (Scenic Point), above Two Medicine Valley, Glacier National Park.

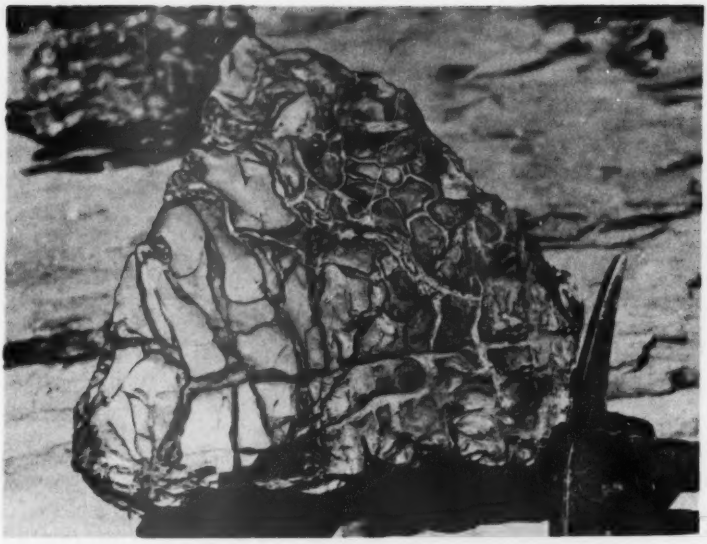
PLATE 8. SEDIMENTARY STRUCTURES

FIGURE 1.—SUBAQUEOUS MUD CRACKS

In the Sheppard, near Granite Park, Glacier National Park. Polygons are dolomite; interstices are limestone. There is little evidence of secondary segregation.

FIGURE 2.—SUBAQUEOUS MUD CRACKS

Filled with edgewise mud breccia of dolomite and limestone pebbles in limestone matrix. Sheppard; moraine at Iceberg Lake, Glacier National Park.



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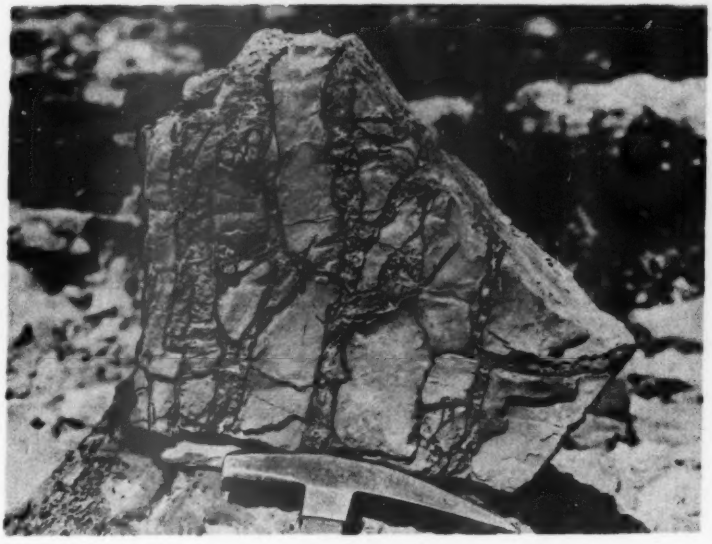

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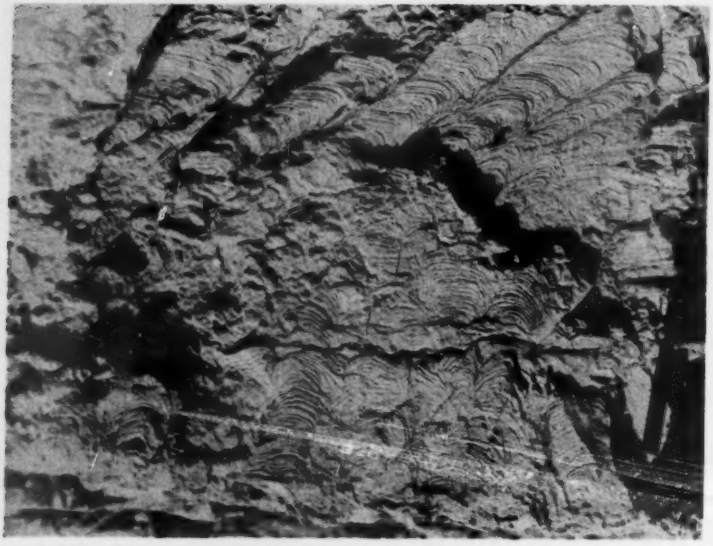
SEDIMENTARY STRUCTURES



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BELT ALGAE

PLATE 9. BELT ALGAE

FIGURE 1.—COLLENIA COLUMNARIS FENTON AND FENTON

Vertical and oblique colonies forming massive beds in the C. columnaris biostrome of the Altyn (Hell Roaring) at the foot of Mt. Appekunny, Glacier National Park.

FIGURE 2.—COLLENIA COLUMNARIS FENTON AND FENTON

Colonies which grew without crowding, in another part of the same biostrome.

PLATE 10. BELT ALGAE

FIGURE 1.—COLLENIA WILLISII N. SP.

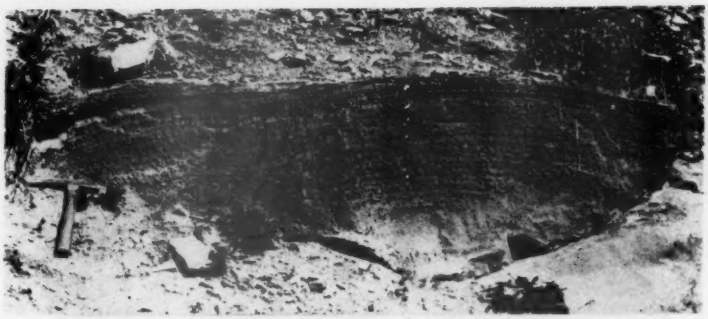
Natural section of a specimen, 66 inches in diameter. Siyeh (upper Goathaunt) on trail near Piegan Pass, Glacier National Park.

FIGURE 2.—COLLENIA SYMMETRICA FENTON AND FENTON

Natural section of an isolated colony in which the laminar structure is not preserved. Siyeh (C. symmetrica zone) at Dawson Pass, Glacier National Park.

FIGURE 3.—COLLENIA WILLISII N. SP.

Upper surface of a complex of colonies whose width approximates 10 feet. Siyeh (Granite Park), Hole-in-the-Wall Basin, Glacier National Park.



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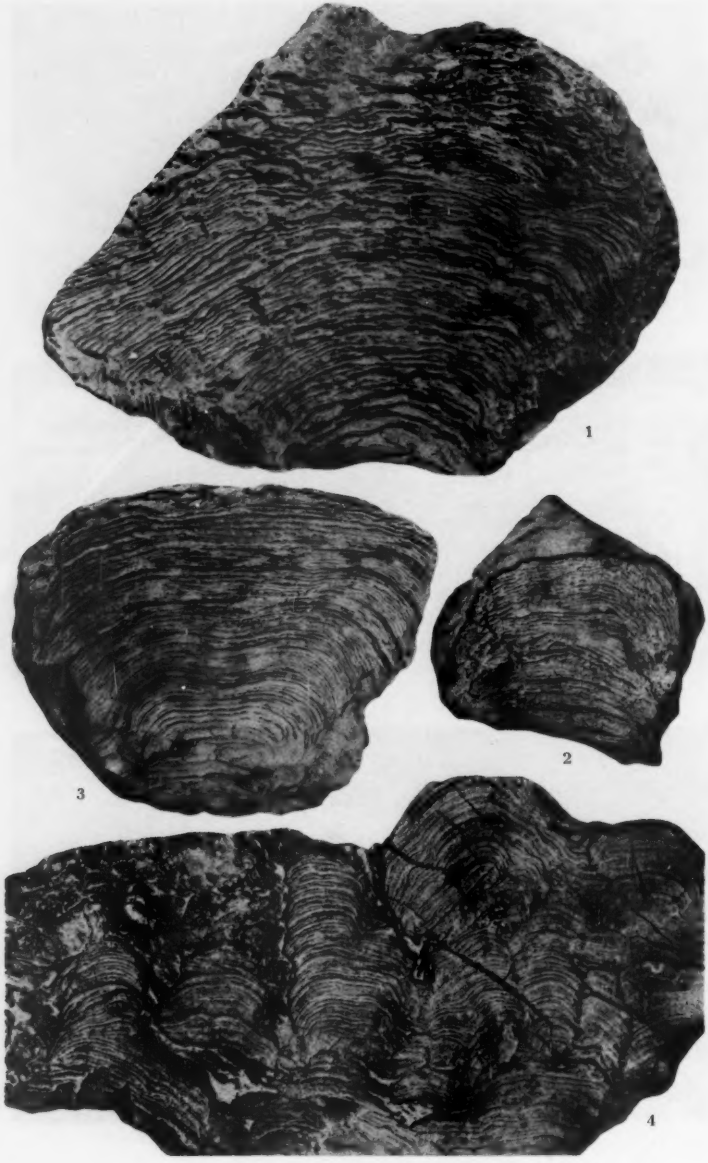
BELT ALGAE



BELT ALGAE

PLATE 11. BELT ALGAE

FIGURE 1.—COLLENIA WILLISII N. SP.

Natural section of the holotype, from the Siyeh (Goathaunt), drift at Iceberg Lake, Glacier National Park. ×0.33. (Princeton University.)

FIGURE 2.—COLLENIA ALBERTENSIS N. SP.

Natural section of the holotype; Altyn (Hell Roaring) north slope of Gable Mountain, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 3.—COLLENIA UNDOSA WALCOTT

Natural section of a colony closely resembling the early stages of *C. willisii* of the type shown on figure 6 of Plate 12. Lower Spokane, near Granite Park, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 4.—COLLENIA UNDOSA WALCOTT

Natural section from a typical compound colony whose total width is about 50 inches. Lower Spokane, junction of Garden Wall and Granite Park-Logan Pass trails, Glacier National Park. ×1. (Princeton University.)

PLATE 12. SEDIMENTARY STRUCTURES AND ALGAE

FIGURE 1.—IRREGULAR "STORM ROLLERS"

From Grinnell, Cobalt Lake, near Two Medicine Pass, Glacier National Park. ×0.25.

FIGURE 2.—SUBOVATE MUD BALL ("STORM ROLLER")

From Grinnell, Cobalt Lake, near Two Medicine Pass, Glacier National Park. ×0.25.

FIGURE 3.—MUD CRACKS IN RED ARGILLITE

Quartzite fillings. Grinnell, Cobalt Lake, near Two Medicine Pass, Glacier National Park. ×0.25.

FIGURE 4.—COLLENIA WILLISII N. SP.

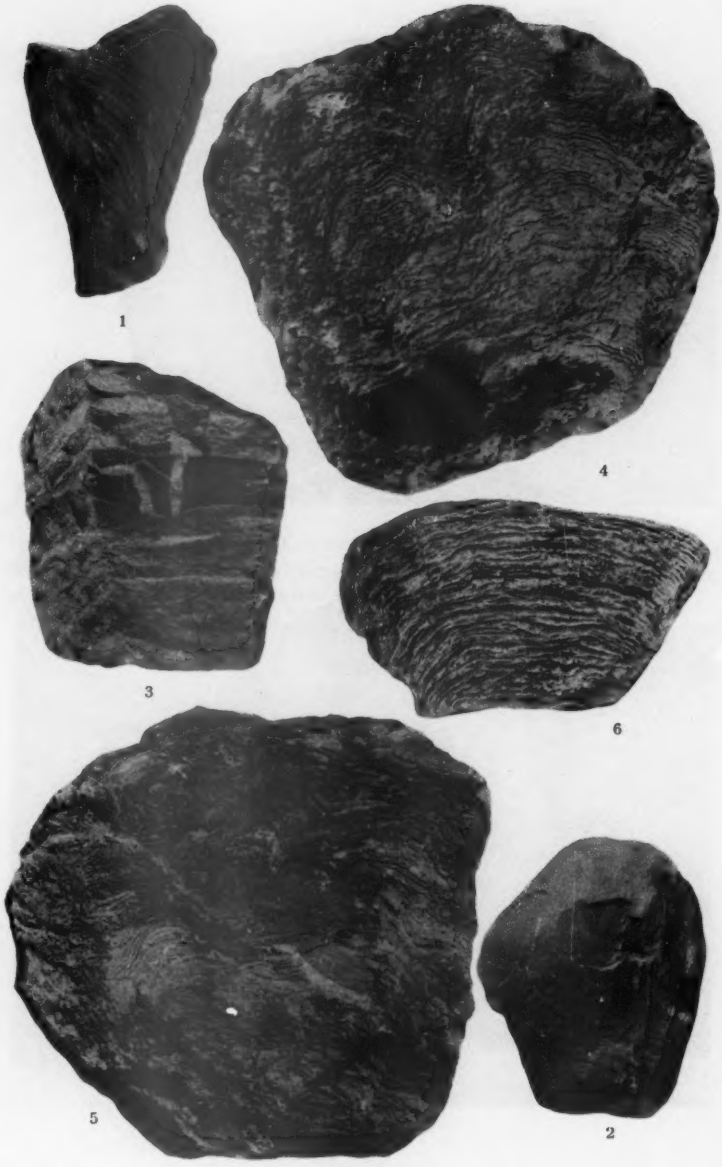
Paratype, showing fusion of three colonies into one. Siyeh (Goathaunt), Iceberg Lake. ×0.33. (Princeton Universtiy.)

FIGURE 5.—COLLENIA WILLISII N. SP.

Reverse of specimen shown in figure 4, displaying crumpled laminae. ×0.33.

FIGURE 6.—COLLENIA WILLISII N. SP.

Basal portion of a colony overlying one of those shown in figure 3 of Plate 10. ×0.75. (Princeton University.)



SEDIMENTARY STRUCTURES AND ALGAE

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BELT ALGAE

PLATE 13. BELT ALGAE

FIGURE 1.—COLLENIA CLAPPII N. SP.

Upper surface of a concavo-convex colony. Siyeh (Goathaunt) talus at Indian Lake, Glacier National Park.

FIGURE 2.—COLLENIA SYMMETRICA FENTON AND FENTON

Part of a stratum (biostrome) formed by this species. Siyeh (C. symmetrica zone), Cut Bank Pass, Glacier National Park.

PLATE 14. BELT ALGAE

FIGURE 1.—COLLENIA CLAPPII N. SP.

Natural section of the holotype, showing red mud laminae. Lower Kintla, near Boulder Pass, Glacier National Park. ×0.5. (Princeton University.)

FIGURE 2.—COLLENIA VERSIFORMIS N. SP.

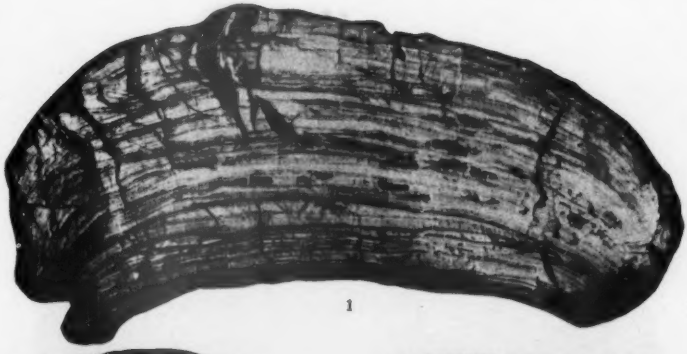
Columnar ecad of this species, in a form virtually identical with *C. albertensis* n. sp. The matrix is an edgewise mud breccia in which the pebbles are limestone and matrix is dolomite. Holotype. ×0.5. (Princeton University.)

FIGURE 3.—COLLENIA UNDOSA WALCOTT

Part of a large, compound colony. The underlying dolomitic sandstone bears stylolites. Much reduced. Spokane, Garden Wall, Glacier National Park.

FIGURE 4.—COLLENIA PARVA N. SP.

Portion of the holotype, showing small typical colonies. Sheppard, Boulder Pass, Glacier National Park. ×1. (Princeton University.)



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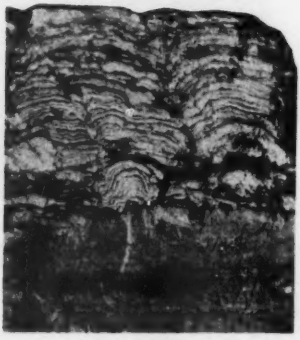

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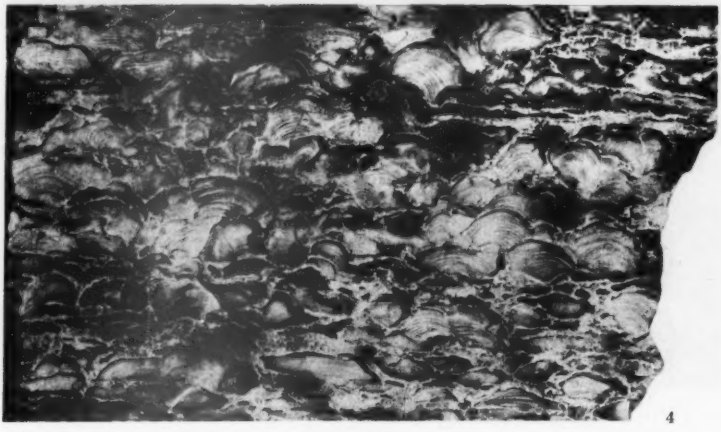

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BELT ALGAE

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BELT ALGAE

PLATE 15. BELT ALGAE

FIGURE 1.—COLLENIA FREQUENS WALCOTT

Natural section of a typical, conical specimen. Siyeh (C. frequens zone) near Swiftcurrent Pass, Glacier National Park. ×0.45. (Princeton University.)

FIGURE 2.—COLLENIA FREQUENS WALCOTT

Natural sections of this species in a block from the upper beds of the C. frequens zone in Hole-in-the-Wall Basin, Glacier National Park.

PLATE 16. BELT ALGAE

FIGURE 1.—COLLENIA EXPANSA N. SP.

Weathered vertical section through the holotype, showing mammillae and layers composed of thin laminae. Missoula group: limestone approximately equivalent to the Hellgate quartzite. From ridge 2 miles northeast of Steamboat Mountain, north of North Fork of Dearborn River, Montana. ×1. (University of Montana.)

FIGURE 2.—COLLENIA EXPANSA N. SP.

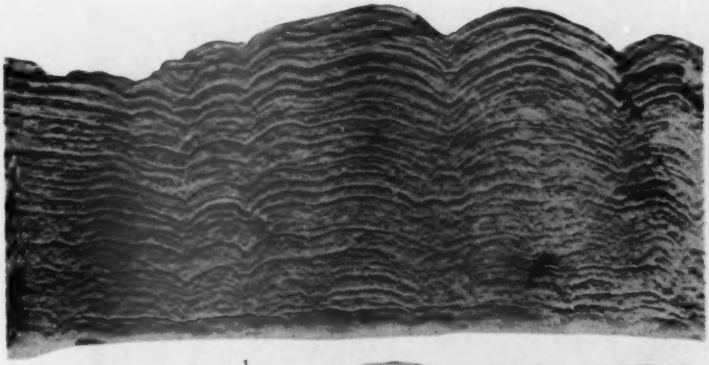
Under surface of a layer in the paratype, showing mammillae. Locality and horizon as for figure 1. ×1. (University of Montaina.)

FIGURE 3.—COLLENIA EXPANSA N. SP.

Vertical section through a mammilla of the holotype, showing indistinct pillars. ×7.5.

FIGURE 4.—COLLENIA VERSIFORMIS? N. SP.

Part of a colony doubtfully referred to this species. Upper Helena, Ford Creek, Cooper's Lake quadrangle, Montana. ×0.5. (University of Montana.)



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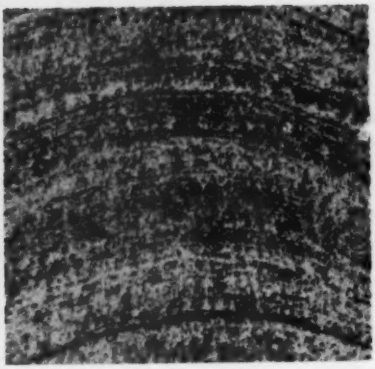


3

BELT ALGAE

ALGAL BIOHERMS OR REEFS

PLATE 17. ALGAL BIOHERMS OR REEFS

BASAL GRANITE PARK MEMBER OF THE SIYEH

Going-to-the-Sun Highway, 6.4 miles northwestward from Logan Pass. At the base in the upper part of the first bioherm; above it, the second, with depressed beds and off-reefs. The third bioherm appears at the top; it shows variations in *Collenia versiformis* n. sp. The first and second bioherms are composed of ecads A and D (Fig. 19) of C. *frequens* Walcott.

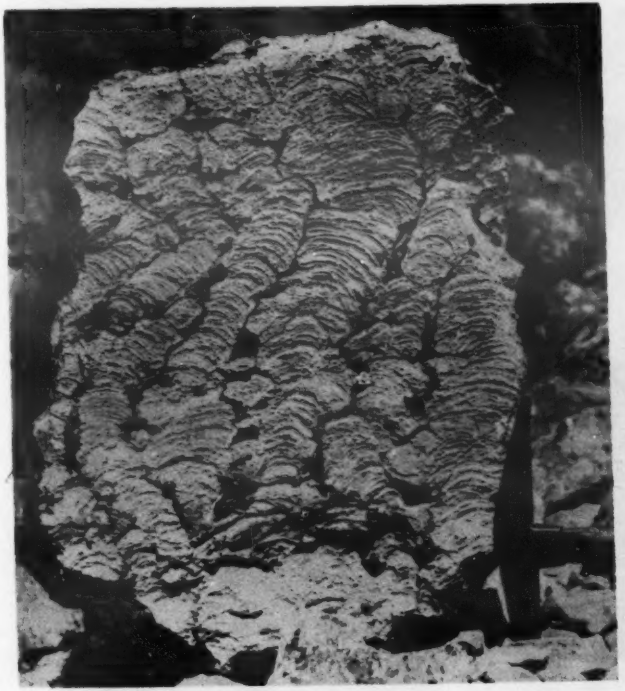
PLATE 18. BELT ALGAE

FIGURE 1.—COLLENIA VERSIFORMIS N. SP.

Natural section of several colonies. Siyeh (C. frequens zone) at Iceberg Lake, Glacier National Park.

FIGURE 2.—FUSION OF COLUMNAR COLONIES

C. versiformis in expanded colonies resembling those to which Walcott applied the name *C. compacta*. Siyeh (C. frequens zone), near falls in Hole-in-the-Wall Basin, Glacier National Park.



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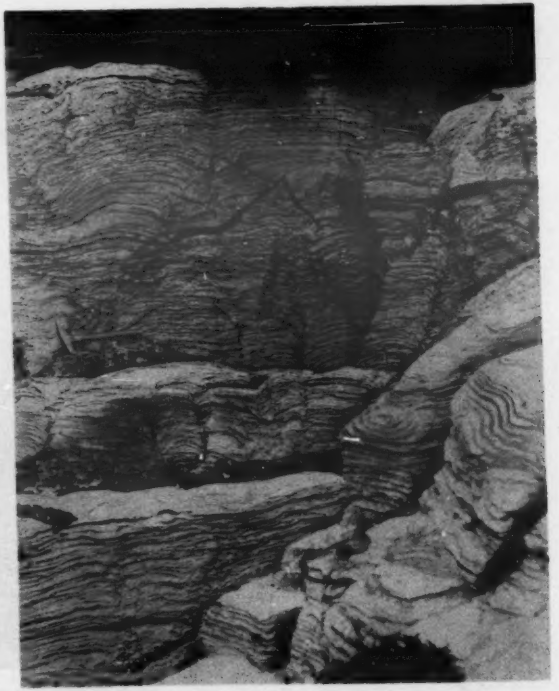

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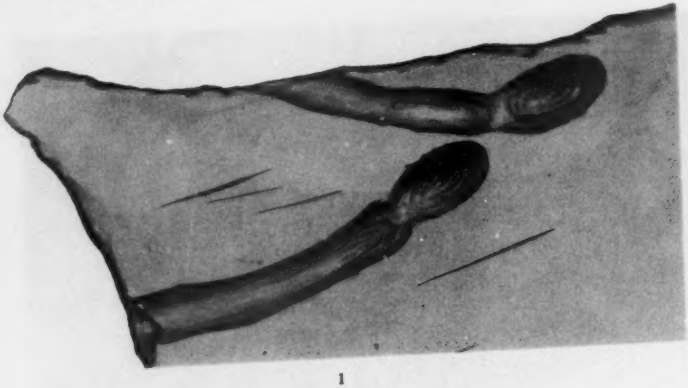

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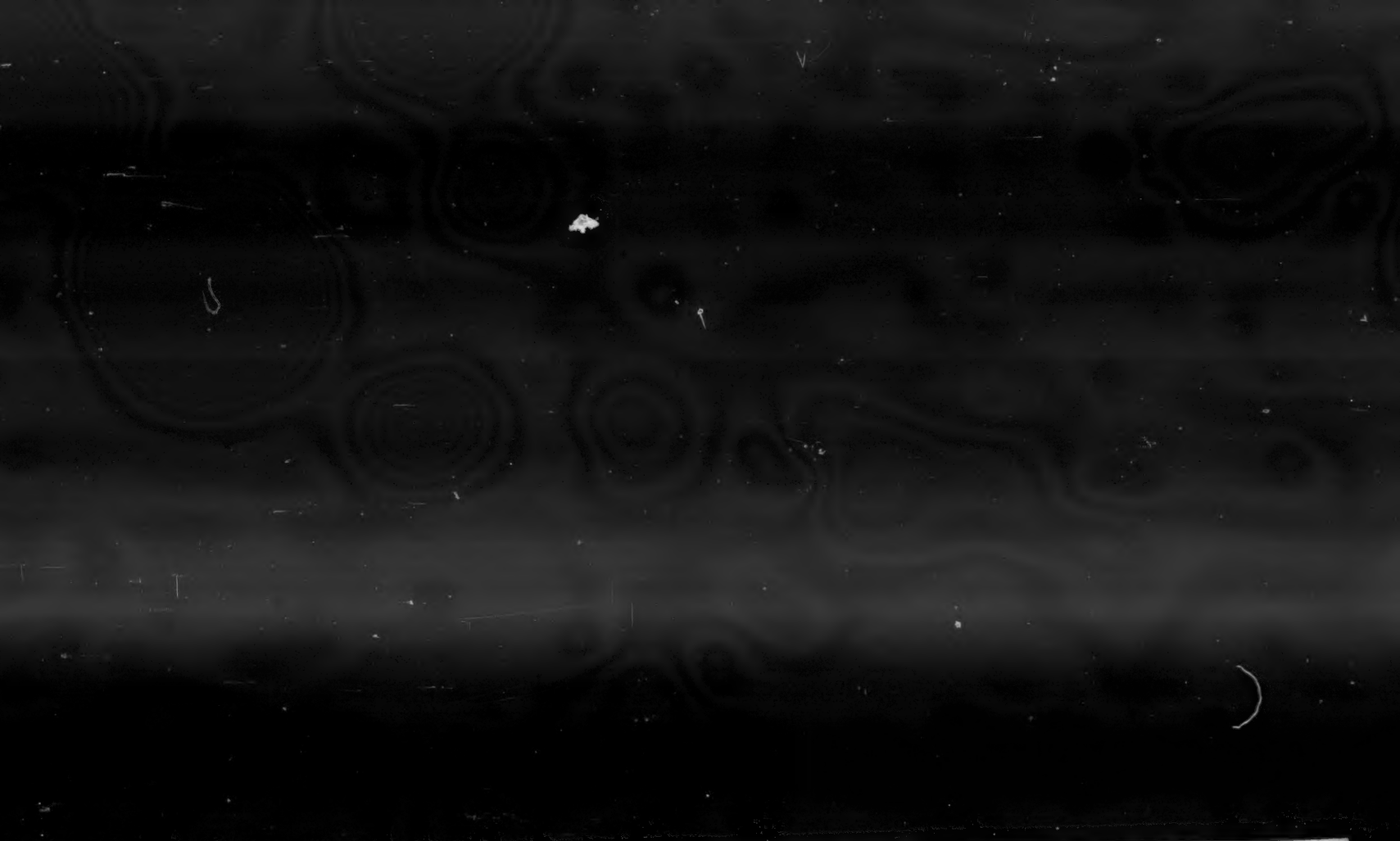
TRACES OF ANIMALS

PLATE 19. TRACES OF ANIMALS

FIGURE 1.—TRACES RESEMBLING TRAILS AND BURROWS OF PELECYPODS
Siyeh (C. symmetrica zone), Dawson Pass. ×1. (Princeton University.)

FIGURE 2.—ANNELID BURROWS IN BROWN QUARTZITE
Siyeh (C. symmetrica zone), near Dawson Pass. (Princeton University.)



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QUATNY
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Miocene Santa Inés Formation Tsi
Oligocene Carapita Formation Tc
Eocene Merecure Formation Tm
Cret-Terty Santa Anita Formation KTsa
Upper Guayuta Group
San Antonio Formation Ksao
Querecual Formation Kq
Middle Bergantín Beds Kb
Sample Numbers E-291, S-2578 etc.
Vertical Beds
Overturned Beds
Trace of individual Beds
Formation Boundaries
Origin of coordinates -Barcelona- N. 300,000 E. 500,000
CONTOURS IN METERS
Vertical interval 20 or 100 ms.
Co. San Andrés
Co. San Juan
R. San Juan
Ksao
KTsa
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Q. Hacienda
R. Lo
Co. Cambural
Qda
Co. Escurotes
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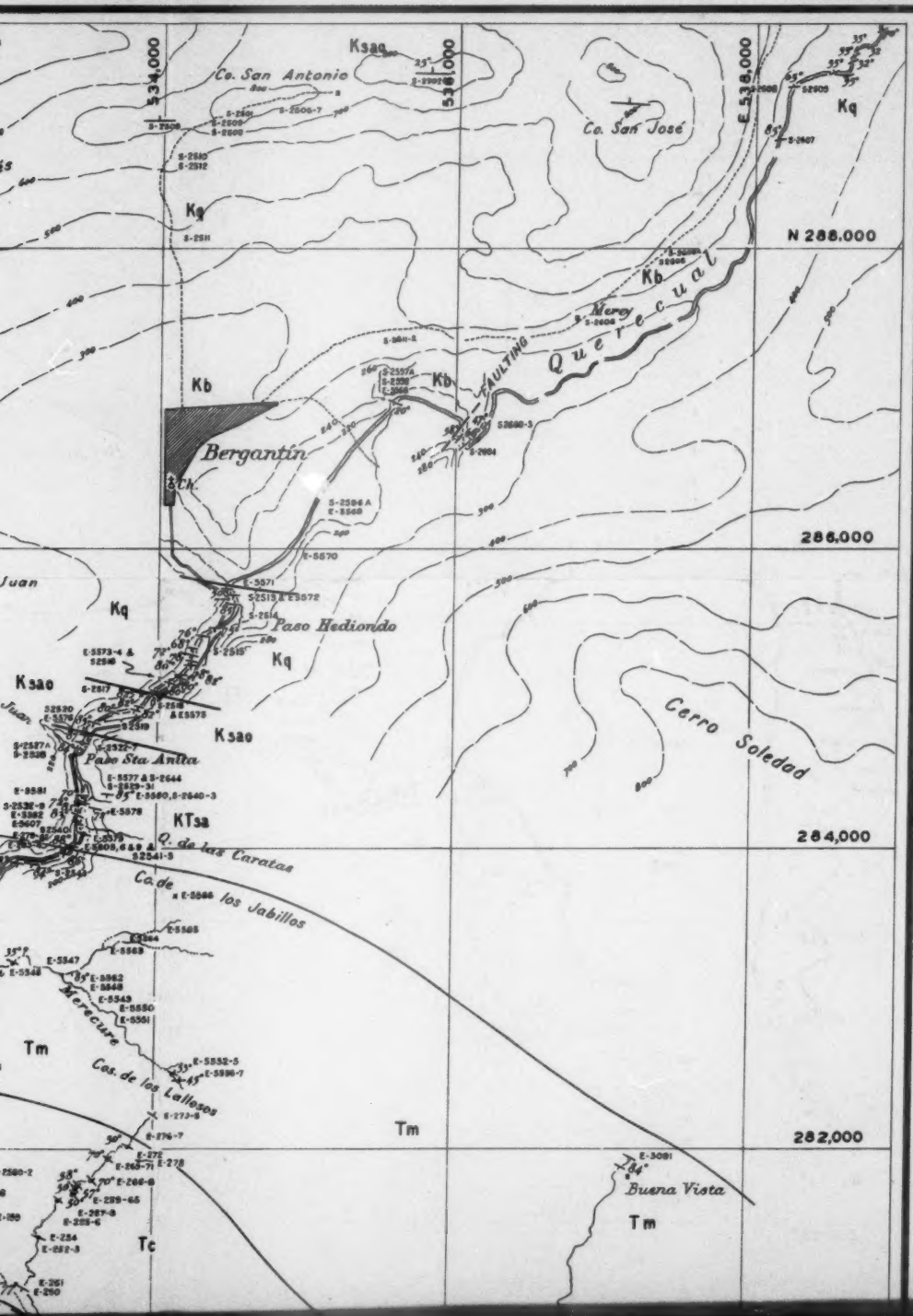
Capaya
auto-ra from Barcelona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Buena Vista
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GEOLOGICAL MAP OF

BERGANTÍN - SANTA INÉS AREA

SHOWING FORMATIONS EXPOSED ON

RIO QUERECUAL & ITS TRIBUTARIES

DISTRICT OF LIBERTAD STATE OF ANZOÁTEGUI

VENEZUELA

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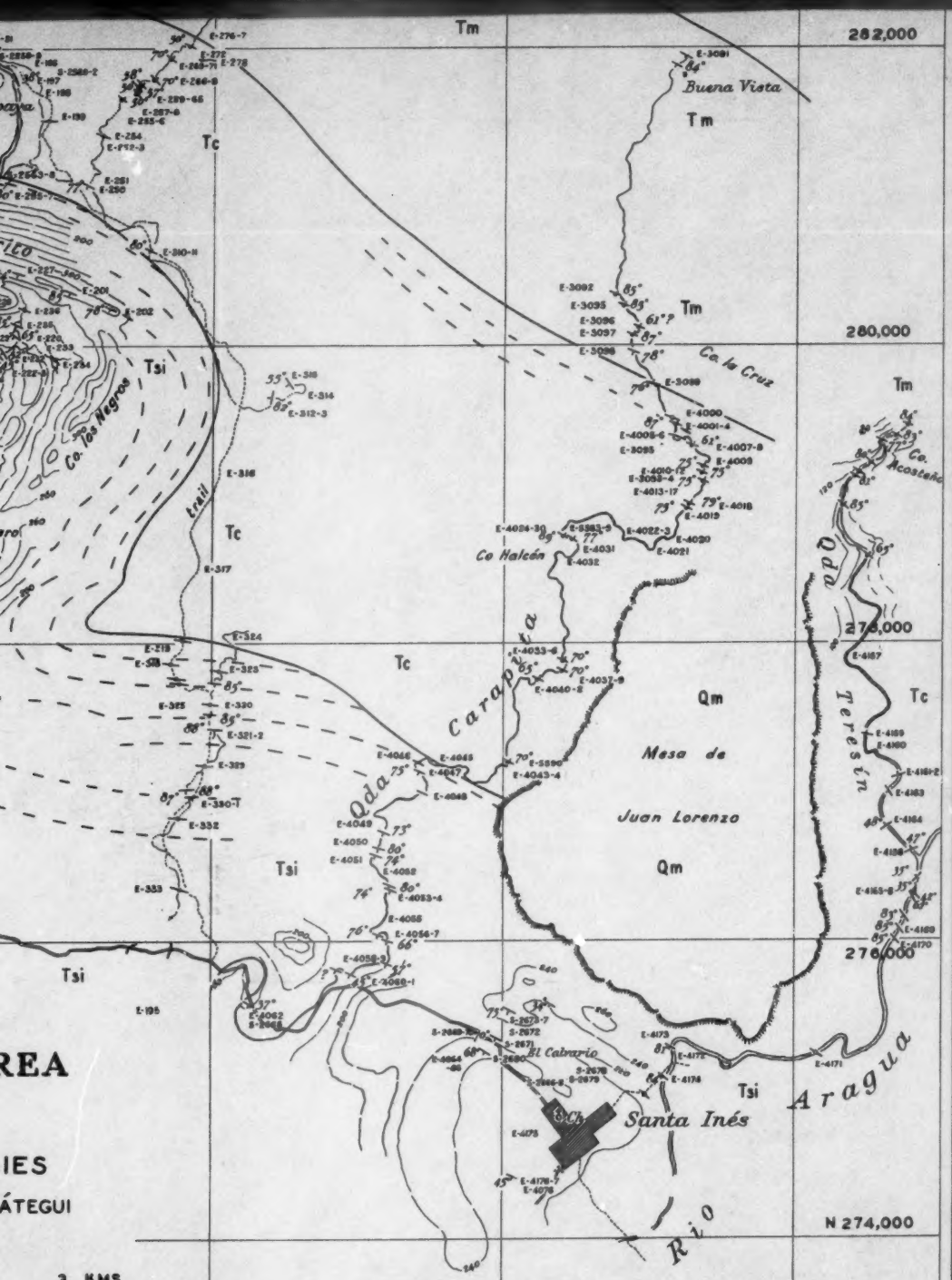
GEOLOGICAL MAP OF THE BERGA



THE BERGANTIN-SANTA INES AREA, VENEZUELA

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 48, PP. 1971-2024, 9 PLS., 2 FIGS. DECEMBER 1, 1937

STRATIGRAPHY OF THE RIO QUERECUAL SECTION OF NORTHEASTERN VENEZUELA

BY HOLLIS D. HEDBERG

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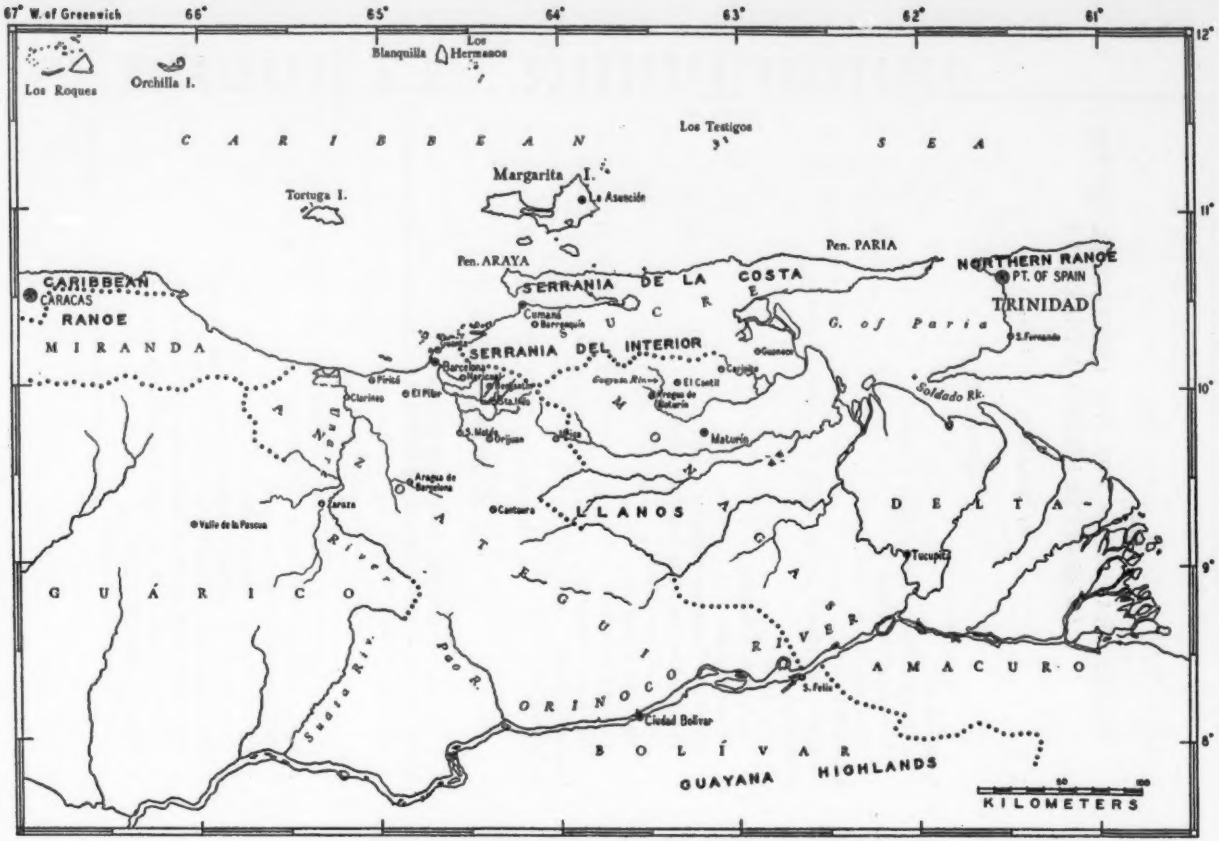

FIGURE 1.—*Index map of eastern Venezuela and Trinidad*

INTRODUCTION

GEOLOGIC SETTING OF NORTHEASTERN VENEZUELA

Eastern Venezuela may be divided into three major physiographic and geologic provinces (Fig. 1). The highlands of Venezuelan Guayana south of the Orinoco River are composed largely of igneous and metamorphic rocks with some large remnants of pre-Tertiary sediments. Along the northern coast is the Caribbean Mountain system consisting of a narrow coastal belt of metamorphic rocks (Serrania de la Costa) flanked on the south by upturned and folded Cretaceous and Tertiary strata (Serrania del Interior). Between Guayana on the south and the foothills of the Serrania del Interior on the north lie the vast, nearly featureless Quaternary-covered plains of the Venezuelan llanos and the Orinoco delta.

The llanos and delta areas belong to the so-called Orinoco geosyncline [1] which has been the site of marine or brackish-water deposition throughout most of the interval from early Cretaceous to present time. Venezuelan Guayana, on the other hand, is part of the great Guayana Shield—the continental nucleus of northern South America—and has been dominantly a land area since the Paleozoic era. Another land area appears to have existed to the north of the geosynclinal trough during Tertiary and perhaps Cretaceous time. The presence of this northern borderland to which Guppy [2] has given the name of Paria [3] is required by the evident derivation from the north of much of the sedimentary filling of the geosyncline. Originally, Paria probably lay well beyond the limits of the present coast line of South America but in later Tertiary time may have extended as far south as the area of the Serrania de la Costa. The Serrania del Interior is the northern and originally axial portion of the Tertiary stage of the Orinoco geosyncline, folded, faulted, and uplifted by late Tertiary orogeny which has involved the relative movement of Paria toward the Guayana Shield and the shifting of the geosynclinal axis southward to its present position beneath the llanos and the Orinoco delta.

The record of the early (pre-Cretaceous) geologic history of eastern Venezuela has been lost through erosion or is hidden in the metamorphic and igneous complexes of the Guayana Shield (and perhaps of the Serrania de la Costa). Cretaceous, Tertiary, and Quaternary rocks are almost the only unmetamorphosed sediments of the region. In the great llanos and delta areas and along the borders of the Guayana Shield only Quaternary

[1] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928) p. 364. J. P. MacGowan, Fort Worth, Texas.

[2] R. J. L. Guppy: *On the geology of Antigua and other West Indian islands with reference to the physical history of the Caribbean region*, Geol. Soc. London, Quart. Jour., vol. 67 (1911) p. 681-700.

[3] Charles Schuchert: *Geological history of the Antillean region*, Geol. Soc. Am., Bull., vol. 40 (1929) p. 339; *Historical geology of the Antillean Caribbean region.* (1935) p. 680. John Wiley and Sons, New York.

FIGURE 1.—*Index map of eastern Venezuela and Trinidad*

sediments appear at the surface, and the presence of older strata here is known only through well borings. At the north edge of the basin, however, Cretaceous and Tertiary strata have been brought to the surface in the rugged Serrania del Interior, and in this range lies the most available key to the later history of the region.

PURPOSE OF THIS PAPER

Relatively little has been published on the geology of northeastern Venezuela. Only the general outlines of stratigraphy and structure are known, and even adequate base maps are lacking. During the last 10 or 15 years the region has been visited by many geologists engaged in petroleum exploration work; considerable information is now stored in the files of the several oil companies which have or have had interests in this part of the country. Commercial geological exploration will probably continue here for many years and, as the need for secrecy becomes less, more and more of the results will be made public. One of the purposes of the recently organized Servicio Geologico of the Venezuelan Government is to coördinate and make available the non-commercial geological data obtained by private companies. The region is large; it is relatively accessible; and it is important not only as a key to the more complicated adjoining areas of Trinidad and central Venezuela but also in its bearing on the interpretation of the geological development of the greater Caribbean region and northern South America. It will undoubtedly provide much interesting and valuable information in the coming years.

An essential prerequisite to progress in the geological study of a region is the establishment of a standard stratigraphic section—a section in which there is general agreement as to the names and limits of stratigraphic units and in which these units are well exposed and in normal relation to overlying and underlying units. Such standard reference sections provide a means by which the work of different investigators can be coördinated and made a significant part of the gradually accumulating sum of geological information on the region. The advantage of establishing standard sections as early as possible in the course of geological investigation is obvious. Although opinions on age, ranking, and correlation of stratigraphic units will naturally change with time, the standard section will constitute from the beginning a relatively stable base which will permit reference to definite geographic and geologic limits.

Because of structural complications, continuous stratigraphic sections are difficult to find in the Serrania del Interior; and along much of the mountain front the younger part of the Tertiary section is completely overlapped by Quaternary deposits. A number of formation names have already found their way into the published literature on this region, but,

for most of these, type sections have not been accurately designated, and the limits of the formations have been poorly defined. Several units worthy of formation rank have never been named. The most complete and most regular section known to the writer in this region is that exposed on the Rio Querecual and its tributaries in the northeastern part of the State of Anzoategui. The purpose of the present paper is to describe this section and divide it into clearly defined and adequately characterized stratigraphic units with the hope of making it a standard reference section for the region.

SOME STRATIGRAPHIC PRINCIPLES

Since there is considerable variation in opinion with regard to procedure in stratigraphic classification and the usage of certain stratigraphic terms, it seems desirable to preface the discussion of a proposed standard section with a brief outline of some principles and definitions accepted by the writer.

A geologic *formation* is a lithogenetic unit. It should consist of rocks of one lithologic type or of an alternation of different types, representing the deposits of a particular environment of deposition or an alternation of such environments, and it should be unbroken by unconformities or hiatuses of major rank. It should be a mappable unit and at the same time should possess characters which will allow its definition in well or pit sections. Lithologic criteria for formation division should be chosen not only with reference to their prominence but also with particular attention to their significance as concerns environment of deposition or conditions of origin.

All formations are limited in lateral extent. One formation may grade laterally into another, two different formations may represent the same time interval in adjacent areas, and the age of a formation may vary from place to place. Formations may be subdivided, on the basis of minor differences in lithology, mode of origin, or time of origin, into *members*. Several stratigraphically adjacent formations with important features in common may be included in a *group*. Groups may conceivably overlap, depending on the features considered in the assembling of their constituent formations.

A formation should be named from a geographical feature within its outcrop area and preferably in or near its type section. Priority in publication shall generally be accepted in determining the name of a formation, but only where the published name is accompanied by an adequate description and designation of a type section. Unsatisfactory names should not be retained merely because they have been mentioned in published literature. The proposal of a formation name should at the minimum be accompanied by a statement of the source of the name, a designa-

tion of a type locality, a definition of the upper and lower limits of the formation (both geographic and geologic), and a summary of its lithologic character.

Inasmuch as a formation usually contains sediments closely associated both in time and manner of origin, its boundaries frequently though not necessarily coincide with those of paleontologic and mineralogic (or petrographic) units. However, while paleontology and mineralogy may serve as valuable aids in identifying a formation, they should always be subordinated to lithology in its definition. Paleontologic and mineralogic (or petrographic) units should be kept nomenclatorially distinct from lithologic units (formations). Thus the paleontologic stratigraphic unit is the *faunizone*[4] and the mineralogic stratigraphic unit is the *mineral zone*. Faunizones and sub-faunizones may be given arbitrary letters or numbers but are preferably named from some characteristic fossil. Mineral zones may likewise be given arbitrary letters or numbers but are preferably named from characteristic minerals. The boundaries of faunizones and mineral zones may, but do not necessarily, coincide with formation boundaries.

Formations, mineral zones, and faunizones are stratigraphic units into which the time concept enters only secondarily. These units do not represent any definite interval of geologic time and their time values may change from place to place. The unit in the time-stratigraphic category is the *stage*[5] which is independent of lithologic, paleontologic, or mineralogic variation and comprises the sediments deposited in a region during a specific time interval—the geologic *age*. This concept of a material stratigraphic unit bounded only by time lines but of lower rank than a *series* or a *system* is believed to be of fundamental importance in stratigraphy. A stage should, where possible, be based on the well-defined type section of a marine fossiliferous formation (or group) and should bear the name of that formation. It is to some extent possible to correlate the Cretaceous sediments of Venezuela with the recognized stages of Europe and North America but in the case of Tertiary sediments such correlations are usually still very uncertain.

Terms of the standard time scale (Oligocene, early Eocene, etc.) are convenient as a means of expressing opinions on the approximate or relative geologic age of sediments. Their value lies particularly in the fact that they are in use throughout the whole world. However, since there is

[4] A faunizone has been defined as a bed or group of beds characterized by an assemblage of organisms, one of which is chosen as index species (or index genus) and gives its name to the unit although it need not be confined to this unit or found in every part of it. For a discussion of this and other zone-terms, *see* W. J. Arkell: *The Jurassic system in Great Britain* (1933). Clarendon Press, Oxford.

[5] H. G. Schenck, H. D. Hedberg, and R. M. Kleinpell: *Stage as a stratigraphic term* [abstract], Am. Geol., vol. 64, no. 1 (1934) p. 70; Geol. Soc. Am., Pr., 1935 (1936) p. 347-348.

much difference of opinion as to their scope even in the region where most of them originated (western Europe), it is impossible that they should have any very exact significance in northern South America. They are used only in a broad and very indefinite sense in this paper.

ACKNOWLEDGMENTS

The geological field work upon which this paper is based was carried out by the writer during brief trips to the Bergantin-Santa Ines area in 1930, 1933, and 1936. Arne Birketvedt, Henry C. Lay, and Frances Hedberg assisted at different times in the mapping of the area by plane table and range finder traverse.

Laboratory work on samples collected in this area was carried out largely in the Geological Laboratory of the Venezuela Gulf Oil Company in Maracaibo, Venezuela. During the course of this work, the writer has benefited from the suggestions of his associates in the laboratory, C. W. Flagler and L. C. Sass.

Special studies of certain phases of the paleontology and mineralogy of the Rio Querecual section were made at Stanford University in 1935. The writer is particularly indebted to H. G. Schenck of this university for constant encouragement and helpful criticism during the course of the work. Eliot Blackwelder and A. F. Rogers also furnished valuable suggestions and assistance.

In carrying out the paleontologic study connected with this paper, the writer has attempted insofar as possible to compare fossils from the Rio Querecual section with the type material of all previously published work on the paleontology of northern South America and the Caribbean region. He wishes first of all to acknowledge the most valuable assistance of J. A. Cushman in the work on the Foraminifera of the Carapita formation. The writer spent two weeks in checking identifications at the Cushman Laboratory in Sharon, Massachusetts, and has also had the benefit of Dr. Cushman's criticism and suggestions.

Through the efforts of Dr. Schenck, foraminiferal samples (in many cases topotype material) were made available for comparison from California, Colombia, Costa Rica, Mexico, Bonaire, and many classic localities in Europe. R. M. Kleinpell furnished specimens from California and information on the stage classification of the California section. Foraminiferal samples were supplied from Trinidad by P. W. Jarvis and H. Naegelli; from Cuba by D. K. Palmer; and from the Gulf Coast of the United States by J. B. Garrett. H. Kugler and E. Lehner, of the Trinidad Leaseholds Company, Ltd., have given important information on the stratigraphic position of various foraminiferal samples from Trinidad. The collections of the Geological Laboratory of the Venezuela Gulf Oil

Company contain numerous samples of foraminiferal material from Venezuela, Colombia, Trinidad, and other areas in tropical America.

Extensive collections of Tertiary mollusks from the Caribbean region were kindly made available by G. D. Harris of the Paleontological Research Institution, Ithaca, New York. Through the courtesy of J. O. Nomland of the Standard Oil Company of California and Bruce Clark of the University of California at Berkeley, the writer was able to compare Venezuelan specimens with excellent collections of Tertiary mollusks from Colombia. Julia Gardner of the United States National Museum, G. E. Vanatta of the Philadelphia Academy of Natural Sciences, H. Ries of Cornell University, and I. M. Tolmachoff of the Carnegie Institution at Pittsburgh were all of great assistance in making available comparative material from their respective institutions.

Discussion of the Rio Querecual section with Clemente de Juana, who recently worked in this area for the Standard Oil Company of Venezuela, has been very profitable. The writer is indebted to James D. Hedberg for important chemical analyses of a number of rocks and minerals. The manuscript has been read by H. G. Schenck, S. W. Muller, A. F. Rogers, C. F. Tolman, A. C. Waters, and A. O. Woodford, of Stanford University, all of whom have given valuable criticism.

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GEOGRAPHY AND GENERAL GEOLOGY OF THE RIO QUERECUAL SECTION

The stratigraphic section discussed in this paper is exposed on the Rio Querecual and its tributaries some 35 kilometers east southeast of the city of Barcelona in the northeastern part of the State of Anzoategui, Venezuela (Pl. 1 and Fig. 1). The area is relatively accessible. There are two principal towns: Bergantin, with a population of about 800, situated 31 kilometers S. 68° E. of Barcelona; and Santa Ines with a population of about 500, situated 11½ kilometers S. 11° 30′ E. of Bergantin. During the dry season both may be reached by car either from Barcelona or from the roads on the llanos to the south, but during the rainy season, which lasts approximately from August to December, mules and burros constitute the only dependable means of travel.

The countryside is rather sparsely inhabited. Along the main trails and the car road there are a number of houses and clearings and in the bend of the river about midway along the trail between Bergantin and Santa Ines there is a scattered agricultural settlement known as Capaya

or San Antonio de Capaya. The rest of the country is in general heavily wooded although some of the higher hills are bare or only grass covered. Along the river the timber attains a moderate size but away from the streams, especially in the southern part, is is scrubby and includes a large percentage of cactus, thorn bushes, and maya.

The people are as a rule very poor and carry on a hand-to-mouth existence. The principal agricultural products are sugar cane, cotton, casaba, corn, and beans. In the hills about Bergantin where the climate is cooler and the rainfall heavier considerable coffee is grown. Malarial fever is very prevalent and Capaya has several times been destroyed by its ravages. Diseases due to intestinal parasites are also common.

The area lies near the south border of the Serrania del Interior. Bergantin, at the base of the stratigraphic section, has a picturesque setting in a natural amphitheatre just within the edge of the mountains. To the north are the rugged peaks and ranges of the main Sarrania formed largely in Cretaceous sediments and stretching for 40 kilometers northward to the Caribbean Sea. South of the town is the Cretaceous-Eocene range to which belong Cerro Soledad, Cerro San Juan, and Cerro de los Jabillos. This really constitutes the southern limit of the Serrania and from its eminences one may look down over the broad foothill belt of lesser Eocene, Oligocene, and Miocene hills and ridges in which lie the settlements of Santa Ines, Capaya, and San Mateo (Pl. 2, fig. 1). To the south and east across this foothill belt, on a clear day it is possible to discern the faint rim of the Quaternary mesa front, 40 kilometers away.

The large Bergantin anticline, with an approximate trend of N. 75° W., is the southernmost structure of the Serrania del Interior in northeastern Anzoategui. Middle Cretaceous strata are brought to the surface at the crest of this anticline in the vicinity of Bergantin and its steeply dipping southern flank exposes in succession Middle Cretaceous, Upper Cretaceous, Eocene, Oligocene, and Miocene strata. Before the top of the Miocene section is reached the structure reverses, forming the sharp Carata syncline, and southward from here the strata rise over a broad gentle foothills anticline whose axis is 15 to 20 kilometers south of the Bergantin anticline and roughly parallel to it. Only Miocene strata are exposed and the scattered outcrops on its long gentle southern flank supply the upper part of the Miocene section which is missing on the Bergantin anticline.

The Rio Querecual has its headwaters in the mountains northeast of Bergantin and flows southwestward with a moderate gradient across the valley in which the town is situated. It is a small stream, rarely more than 20 meters wide, and except in flood time it may be waded throughout most of its course. At the southern flank of the anticline, it

turns directly across the strike of the nearly vertical Upper Cretaceous and Lower Eocene sediments and, flowing with greatly increased gradient, breaks through the south rim of the Bergantin valley forming the deep gorge separating Cerro Soledad on the east from Cerro San Juan on the west (Pl. 2, fig. 2). Exposures are excellent here as far south as the top of the San Juan sandstone member of the Santa Anita formation but just below this point the stream is choked with huge sandstone boulders and the section is largely covered for several hundred meters, beyond which the uppermost part of the formation is again well exposed.

About 2½ kilometers south of Bergantin there is another rock gorge with rapids and waterfalls where the stream cuts through the thick basal sandstone of the Upper Eocene Merecure formation (Pl. 7, fig. 3). This sandstone, which forms the prominent Cerro de los Jabillos ridge to the east, is followed on the river by a long stretch without outcrops. Upper Merecure sandstones are exposed on the east bank of the river north of Capaya where the stream cuts through the gap between Cerro de los Lallosos and Cerro Cambural, but the intervening section is largely covered except for outcrops on Quebrada Merecure, a tributary which enters from the east in this interval. Strata in the Merecure formation show a steep north dip, due to overturn.

After passing through the sandstones of the lower part of the Oligocene Carapita formation the river makes a large eastward bend in the dominantly shaly upper part of this formation but turns back westward along the base of the high ridges of nearly vertical Miocene sandstone and conglomerate (Cerro Potrerito) of the Santa Ines formation. Southwest of Capaya it breaks through these ridges in a long defile cutting directly across strike and then angles southwestward in a higher part of the Santa Ines formation until it finally flows westward out of the area in the broad strike valley between the Fila de Uchirito on the north and the prominent sandstone hills of the Carata syncline on the south.

The normal structure of the southern flank of the Bergantin anticline is disturbed in the vicinity of Capaya by a somewhat anomalous feature known as the Capaya Z-flexure. This structure is clearly manifested in the trace of the prominent sandstone and conglomerate ridges which form the basal part of the Santa Ines formation. West of the river these make up the prominent Fila de Uchirito, strike ridges of nearly vertical strata striking N. 80° W. for 25 kilometers. These ridges are broken by the Rio Querecual southwest of Capaya but continue for a short distance east of the river as Cerro Potrerito and other parallel ridges. They are then bent acutely southward in a true Z-flexure although the strata still maintain their nearly vertical attitude. The length of the diagonal of the Z is about 4 kilometers and the ridges then resume their former strike

FIGURE 1. SOUTHERN FRONT OF SERRANIA DEL INTERIOR NEAR SANTA INES
Successive ridges formed by (a) Cretaceous, (b) Eocene, (c) Oligocene, and (d) Miocene strata.

FIGURE 2. VALLEY OF RIO QUERECUAL
Looking northward from Capaya toward Bergantin.

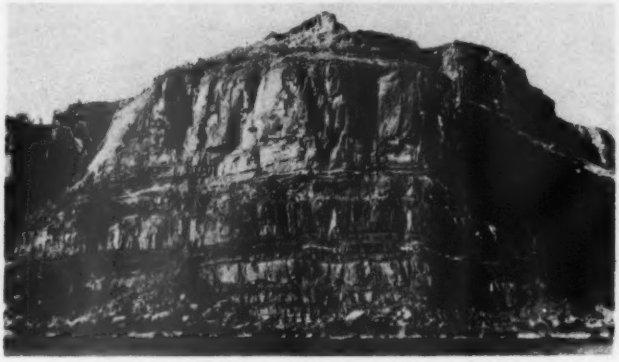

FIGURE 3. MASSIVE SANDSTONES AND VARICOLORED SHALES
Barranquin formation on Puinare Island near the seaport of Guanta.

RIO QUERECUAL AREA — BARRANQUIN FORMATION

FIGURE 1. THIN-BEDDED CARBONACEOUS LIMESTONE ON RIO QUERECUAL

FIGURE 2. DEFLECTION OF BEDDING
Both above and below characteristic discoidal limestone concretions of Querecual formation (Picture is of time-equivalent La Luna formation).

FIGURE 3. FINE AND REGULAR LAMINAE IN QUERECUAL LIMESTONE
Commonly 15 to 30 to the inch. Note concretion at head of hammer.

of N. 80° W. and continue eastward with gradually diminishing dip for many kilometers past the town of Santa Ines.

This remarkable structure is clearly brought out in the aerial photographs of the region and it is noteworthy that while the offset in the Santa Ines ridges amounts to several kilometers, the reflection of the Z-flexure in the older sandstone ridges of the Merecure formation north of Capaya is discernible only as a faint bending of the strike. The distortion so evident in the younger formation has apparently been almost entirely absorbed by flowage in the incompetent Carapita shale separating these two competent sandstone units. Partly on this account, the Carapita formation exposed in the Rio Querecual in the vicinity of Capaya is less than half the thickness of the same formation 5 kilometers to the east in Quebrada Carapita, a tributary of the Rio Querecual. Because of the evident distortion of the formation in the river section and the scarcity of outcrops and poor preservation of fossils there, the section on Quebrada Carapita rather than that on the river is considered as the type for the formation.

The Miocene Santa Ines formation is the thickest of those represented in this area. However, only the basal part is exposed on the Rio Querecual and in order to complete the standard section it is necessary to include outcrops in the hills and streams southward from Santa Ines and the Rio Querecual to the vicinity of San Mateo, a town 36 kilometers S. 32° W. of Bergantin and 46 kilometers S. 18° E. of Barcelona. This portion of the formation forms the prominent Cerro Grande and other hills along the Carata syncline and covers the whole broad anticlinal structure to the south. The top of the formation is made up of the sandy limestones which hold up the long strike ridge east of San Mateo, known as Cerro Los Dividives.

STRATIGRAPHY

INTRODUCTION

The Cretaceous and Tertiary sediments of northeastern Venezuela have a total thickness of more than 40,000 feet. The standard section exposed on the Rio Querecual and its tributaries is some 28,000 feet thick, as calculated by the Hewett[6] method. To this figure may be added 10,000 to 15,000 feet belonging to the Santa Ines formation south of the river section and an undetermined thickness of Pliocene strata still farther south. The Lower Cretaceous Barranquin formation, although not outcropping on the Rio Querecual, doubtless underlies this section. It is 3500 to 4500 feet thick and widely exposed elsewhere in northeastern Venezuela.

The following discussion is concerned chiefly with the limits and characteristics of the seven formations recognized on the Rio Querecual and

[6] D. F. Hewett: *Measurement of folded beds*, Econ. Geol., vol. 15, no. 5 (1920) p. 367-385.

its tributaries. Physiographic features, dips and strikes, and formation boundaries are shown on the areal geologic map (Pl. 1). The relation of the lithology of outcropping beds to formation divisions and mineralogic and paleontologic features is shown graphically on the accompanying columnar sections:

Bergantin beds, Querecual formation, San Antonio formation (Pl. 9, sect. A)
Santa Anita formation, Merecure formation (Pl. 9, sect. B)
Carapita formation (Pl. 9, sect. C)
Lower part of Santa Ines formation (Pl. 9, sect. D).

Locations and serial numbers of samples collected for laboratory study are shown both on the map and on the columnar sections.

The writer's acquaintance with the Rio Querecual section began in 1930 when with the assistance of A. Birketvedt he first measured and collected this section. The original data have been supplemented by laboratory study of samples and the results of additional field work in 1933 and 1936. The control for the map and sections is based on plane table survey of the river and range finder traverse of the smaller streams.

Little major faulting has been noted thus far in the Rio Querecual section but it is possible that strike faults exist which may affect the stratigraphic thicknesses given for some of the formations. Much of the section belonging to the Merecure and Carapita formations is overturned so that it is dipping to the north, and some overthrusting may have taken place.

Recent field work has shown a number of cases in which outcrops noted during the first traverse are now covered with debris and where new outcrops have been opened up subsequently by the erosive activity of the streams.

BARRANQUIN FORMATION

NAME AND TYPE LOCALITY: This formation is not exposed in the Rio Querecual area but outcrops over broad areas farther north and east in the Serrania del Interior. As it forms the basal part of the sedimentary section in northeastern Venezuela, it is included here for the sake of completeness.

The type locality is designated by R. A. Liddle[7] as the vicinity of the town of Barranquin, State of Sucre, on the Aragua de Maturin-Cumana trail, from Dos Rios on the south to within 2 kilometers of San Fernando on the north. The formation outcrop is largely limited to the State of Sucre (*see* Fig. 1) but there are some exposures on local structures in northern Monagas and on the islands in the vicinity of Guanta and Puerto La Cruz in northern Anzoategui (Pl. 2, fig. 3). The formation must lie very near the surface at the crest of the Bergantin anticline.

LITHOLOGY: The formation in northeastern Venezuela is described by Liddle[8] as follows:

"Overlying the schists of the Caribbean series, and in northeastern Venezuela outcropping to the south of the schistose rocks which form practically all of the peninsulas

[7] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928) p. 109-111. J. P. MacGowan, Fort Worth, Texas.
[8] *Ibid.*

of Araya and Paria and the area north of El Pilar, are from 3500 to 4500 feet of quartzitic sandstone interbedded with highly arenaceous shale and an occasional limestone bed. . . . On freshly exposed surfaces the sandstones of the Barranquin formation are buff, white or reddish; and the main part of the shales is red, brown, pink, purple, tan, white, or black, depending on the amount of weathering through which they have passed or upon their varying mineral content. . . . The contained iron, which on weathered surfaces stains practically the entire formation red, is chiefly concentrated in hollow ironstone concretions which are scattered through the entire formation. Often there is a distinct pink and red banding both in the sandstones and in the shales. Of the shales, which are interbedded with the sandstones, only a relatively few are black on exposed surfaces; these are concretionary, arenaceous, micaceous and pyritic. Limestones are rare, chiefly occurring near the top of the formation, generally partially metamorphosed, black to dark gray, and full of calcite veins. . . . An average thickness of these limestone beds is less than three feet. There are possibly 400 feet of limestone in the upper half of the Barranquin formation."

The formation is lithologically quite variable but is made up largely of shales of various colors and quartzitic sandstones. Thin limestones, while not predominant, are common in the upper part.

FORMATION BOUNDARIES: The formation supposedly rests unconformably on the metamorphic schists and phyllites of the Caribbean series. The upper limit is rather ill defined but is usually placed arbitrarily at the point in the section where thick Middle Cretaceous limestones first appear above the typical sandstones, shales, and thin limestones of the Barranquin formation.

THICKNESS: Liddle estimates a thickness of 3500 to 4500 feet for the Barranquin formation.

MINERALOGY: A few samples from this formation given heavy mineral study show a very simple zircon-leucoxene detrital mineral suite: leucoxene—4, zircon—4, ilmenite—1, tourmaline—1, rutile—1.[9]

PALEONTOLOGY AND AGE: In 1919 Schlagintweit[10] reported the presence of *Weichselia Mantelli* Seward in black micaceous shale collected by Karsten from near Santa Maria in the State of Sucre. Although the stratigraphic data given for this sample are rather meager it seems probable that it came from below the El Cantil limestone, and from within the Barranquin formation. On the basis of the occurrence of this plant in the Wealden of Europe and also in considerable abundance in beds of Neocomian age in Peru, Schlagintweit considered the beds of Santa Maria as probably Neocomian in age. Dietrich[11] mentions the additional occurrence of *Otozamites* and *Equisetites* in the Karsten samples from Santa Maria and notes that Karsten also reported plant-bearing shales at Barranquin.

Liddle[12] mentions the occurrence of rudistids, *Ostrea* aff. *O. subovata* Shumard, and *Exogyra boussingaulti* d'Orbigny in the upper part of the Barranquin formation at Morro Blanco, 5 kilometers east of Cumana, State of Sucre.

The Cretaceous age of the Barranquin formation is assured from its conformable gradation upward into beds of Middle Cretaceous age (El Cantil formation) and it is probably correctly assigned to the Neocomian stage (Lower Cretaceous).

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[9] Relative abundance of heavy minerals is indicated according to a scale of five: 1—rare, 2—fairly common, 3—common, 4—abundant, 5—flood. A simple zircon-leucoxene detrital heavy mineral suite is one in which zircon and leucoxene predominate although they may be accompanied by minor proportions of such nearly universal detrital minerals as ilmenite, tourmaline, and rutile.

[10] O. Schlagintweit: *Weichselia Mantelli im Nordostlichen Venezuela*, Centralbl. Mineral., Geol., Paleont., nos. 19-20 (1919) p. 315-319.

[11] W. O. Dietrich: *Zur Paläontologie und Stratigraphie der Kreide und des Tertiars in der ostkaribischen Kordillere Venezuelas*, Centralbl. Mineral., Geol., Paläont., no. 6 (1924) p. 182.

[12] R. A. Liddle: *op. cit.*, p. 112.

STRATIGRAPHIC RELATIONS: Early observers such as Wall, Cortese, Dalton, Liddle, and others have almost without exception assigned the metamorphic rocks of the peninsulas of Paria and Araya [13] to the pre-Cretaceous and have assumed that the sediments of the Barranquin formation rested on these schists and phyllites with profound unconformity. The writer has not visited the contact between the Barranquin formation outcrop area and that of the Caribbean series (presumably a fault contact) nor has he studied the metamorphic rocks of the latter series in any detail. According to Liddle [14] this contact may be seen in the neighborhood of El Pilar in the State of Sucre but no evidence of actual superposition of the one over the other is known to the writer.

Trechmann [15] and H. Dighton Thomas [16] have recently brought forth evidence for the Upper Cretaceous age of rocks in the Northern Range of Trinidad, and Kugler [17] states that "as far as is known, the Northern Range is composed entirely of rocks of Cretaceous age". Since the Northern Range of Trinidad is evidently laterally continuous with the Serrania de la Costa of Venezuela (Fig. 1) and since the rocks of the two areas are essentially identical, the acceptance of an Upper Cretaceous age for the metamorphic rocks of Trinidad strongly indicates a similar dating for those of northeastern Venezuela. However, such an age determination involves several difficulties. It is hard to explain the abrupt juxtaposition of highly metamorphosed Upper Cretaceous rocks on the north and unaltered Lower Cretaceous sediments on the south. It is also surprising that none of the fossils typical of the normal Venezuelan Cretaceous section have been identified in the supposed Cretaceous of the Northern Range of Trinidad while none of the fossils found there are known from the normal Cretaceous section of Venezuela. Further investigation of the metamorphic rocks of the Venezuelan mainland and their relation to the unaltered sediments to the south is certainly desirable before their Cretaceous age is definitely accepted, unequivocal as the Trinidad fossil evidence appears to be.

The Barranquin formation grades upward conformably into Middle Cretaceous sediments of the El Cantil formation or the Bergantin beds. The contact is well exposed on the Island of Puinare near the town of Guanta, State of Anzoategui.

CORRELATION: Approximate time equivalents of the Barranquin formation are known in western Venezuela and in Colombia. They include the Segovia series of Dalton [18] in the Carora-Barquisimeto region, which has been described fully by Liddle,[19] the Rio Negro conglomerate of the Sierra de Perija,[20] the so-called Uribante formation of the State of Tachira, and a part of the Giron group of Colombia. The Roraima beds of the Venezuelan Guayana [21] have been considered by some to be the equivalents of the Barranquin formation. The Punceres sandstone of Garner [22] is probably synonymous with the Barranquin formation.

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[13] G. P. Wall: *On the geology of a part of Venezuela and Trinidad*, Geol. Soc. London, Quart. Jour., vol. 16 (1860) p. 460-470.

[14] R. A. Liddle: *op. cit.*, p. 70.

[15] C. T. Trechmann: *Fossils from the northern range of Trinidad*, Geol. Mag., vol. 72 (1935) p. 166-175.

[16] H. D. Thomas: *On some sponges and a coral of Upper Cretaceous age from Toco Bay, Trinidad*, Geol. Mag., vol. 72 (1935) p. 175-179.

[17] H. G. Kugler: *Summary digest of geology of Trinidad*, Am. Assoc. Petrol. Geol., Bull., vol. 20 (1936) p. 1441.

[18] L. V. Dalton: *On the geology of Venezuela*, Geol. Mag., dec. 5, vol. 9, no. 575 (1912) p. 203-210.

[19] R. A. Liddle: *op. cit.*, p. 114-118.

[20] H. D. Hedberg: *Cretaceous limestone as petroleum source rock in northwestern Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 15, no. 3 (1931) p. 229-246.

[21] L. V. Dalton: *op. cit.*, p. 204.

[22] A. H. Garner: *Suggested nomenclature and correlation of the geological formations in Venezuela*, Am. Inst. Min. Metall. Eng., Tr. (April 1926) p. 677.

DISTINGUISHING FEATURES: The principal features of the formation are its quartzitic sandstones and variously colored shales, its great lateral variability, its predominantly clastic character, the presence of thin limestones with Cretaceous fossils in its upper part, and its simple zircon-leucoxene detrital mineral suite.

BERGANTIN BEDS

(Plate 9, section A)

NAME AND TYPE LOCALITY: The lowest stratigraphic division of the Rio Querecual section is poorly exposed and its lower limit is unknown. For this reason it is not given a formation name and the strata which it comprises are designated temporarily as Bergantin beds. These strata are exposed in the vicinity of the town of Bergantin near the crest of the Bergantin anticline and also southward along the Rio Querecual to the base of the black shaly limestone of the Querecual formation, about 250 meters upstream from Paso Hediondo (Pl. 1). The Bergantin beds are stratigraphically equivalent to the El Cantil formation of the State of Monagas and by some might be considered as belonging to that formation. The El Cantil formation has been described in detail by Liddle.[33]

LITHOLOGY: Near the base of the exposed section are dense, medium- to thick-bedded, bluish-gray limestones, some of which are as much as 50 feet thick. These are well exposed in the big bend of the river just northeast of Bergantin and also along the trails to San Antonio and to Mundo Nuevo. Locally they are made up almost entirely of Foraminifera of the genus *Orbitolina* which may readily be seen with the naked eye. Other bluish-gray limestones higher in the section are apparently lacking in *Orbitolina* but carry poorly preserved recrystallized mollusk shells. These limestones are veined with calcite and show distinctive yellowish and brownish discolorations.

Thin-section study of the Bergantin limestones shows that the basal limestones (such as Samples S-2597-A, S-2598, and E-5568, Pl. 9A) are made up in large part of tests of *Orbitolina*, set in a dense impure calcium carbonate matrix (Pl. 4, figs. 1 and 2). There are only occasional recrystallized mollusk shell fragments. Thin sections of some of the higher limestones (Samples E-5567 and S-2596A) show them to be made up largely of small rounded elongate pellets set in a brownish limonitic calcareous matrix. Limestones of this type have been noticed previously in the Cogollo formation of western Venezuela.[34] Many of these higher limestones show coarsely recrystallized mollusk shells and veins of calcite. Sample E-5567 carries numerous specimens of a *Bolivina*-like foraminifer and of encrusting algae. Sample E-5569 is stained with limonite and is very glauconitic.

Light-colored, rather poorly cemented grits and sandstones which weather reddish or yellowish are exposed at a number of horizons in the Bergantin beds. These sandstones are sometimes glauconitic. Most of the section is concealed by the alluvium of the Bergantin valley and, although none was noted in outcrop, it is probable that shale constitutes a large part of these covered intervals.

FORMATION BOUNDARIES: The base of the Bergantin beds is not exposed in this area. The contact with the overlying Querecual formation is localized by the change from gray or blue-gray, massive, fossiliferous limestones and coarse, light-colored sandstones to distinctive dark-gray to black, finely laminated, concretionary, carbonaceous limestones and calcareous shales. The exact contact is not exposed on the Rio Querecual.

[33] R. A. Liddle: *op. cit.*, p. 124-135.
[34] H. D. Hedberg: *op. cit.*, p. 232.

THICKNESS: It is difficult to make an accurate estimate of the thickness of the Bergantin beds because of the lack of outcrops and the scarcity of dips and strikes. Near the crest of the structure dips are gentle but at the base of the overlying Querecual formation they are nearly vertical. Between these points there is little definite information. Assuming a gradual increase in dip the exposed section would amount to about 2900 feet. This figure, however, is very probably too high and it may be that dips continue to be very gentle over most of the outcrop area or that there is duplication of the section by faulting. The thickness of the El Cantil formation is probably only 1000 to 1500 feet.

MINERALOGY: Sandstones in the Bergantin beds show a very simple zircon-leucoxene detrital heavy mineral suite consisting of leucoxene—4, zircon—4, ilmenite—1, tourmaline—1, rutile—1, anatase—0-1, brookite—0-1.

Glauconite occurs in some of the limestones and sandstones.

PALEONTOLOGY AND AGE: The most common fossil in the Bergantin beds of the Rio Querecual section is *Orbitolina concava* (Lamarck) var. *texana* (Roemer). Several species of *Orbitolina* have been described from the western hemisphere but it now seems probable that these are all representatives of *O. concava* (Lamarck). Roemer [25] described *Orbitulites texanus* (=*Orbitolina texana* (Roemer)) from the Cretaceous Glen Rose formation of Texas in 1849 and 1852. In 1926 Carsey [26] named *O. whitneyi* and *O. walnutensis* from the same formation. Vaughan [27] in 1932 stated that *O. whitneyi* Carsey was only a variant of *O. texana* (Roemer). In the same year Silvestri [28] not only placed *O. whitneyi* Carsey definitely in synonymy with *O. texana* (Roemer) but also reduced the latter to a variety of *O. concava* (Lamarck). *O. walnutensis* Carsey was identified by Silvestri as a species of *Dictyoconus*.

With regard to *Orbitolina* in Venezuela, Karsten [29] in 1858 mentions *Orbitulites lenticularis* from Cocharito (=El Cucharito ?), Venezuela, and in 1886 [30] named *Orbitulina venezuelana* from the same locality. In 1924 Dietrich [31] reported on specimens collected by Karsten from various localities in northeastern Venezuela (including the "Plateau of Bergantin") and concluded that they belonged to varieties of *O. lenticularis* (Blumenbach). Silvestri [32] says that *O. lenticularis* (Blumenbach) is very closely related to *O. concava* (Lamarck) and is possibly even synonymous. Although he has not examined Karsten's specimens, he evidently considers it probable that they should be assigned to *O. concava* (Lamarck) var. *texana* (Roemer) rather than to *O. lenticularis* (Blumenbach). Vaughan [33] also considers that *O. venezuelana*

[25] Ferdinand Roemer: *Texas* (1849) p. 392. Bonn.

[26] D. O. Carsey: *Foraminifera of the Cretaceous of central Texas*, Univ. Texas. Bull., no. 2612 (1926) p. 22-23.

[27] T. W. Vaughan: *The foraminiferal genus Orbitolina in Guatemala and Venezuela*, Nat. Acad. Sci., Pr., vol. 18, no. 10 (1932) p. 609-610.

[28] A. Silvestri: *Foraminiferi del Cretaceo della Somalia*, Paleont. Italica, vol. 32 (1932) *Paleontologia della Somalia: Fossili del Cretaceo*, p. 174; *Revisione di Orbitoline Nord-americane*, Pont. Accad. Sci., Mem., vol. 16 (1932) p. 371-394.

[29] H. Karsten: *Uber die geognostische verhaltnisse der westlichen Columbien, der heutigen Republiken Neu-Grenada und Equador*, Amtlicher Bericht 32 Versammlung deutsch. Naturforsch. und Arste zu Wien (1858) p. 80-117.

[30] H. Karsten: *Géologie de l'ancienne Colombie Bolivarienne, Venezuela, Nouvelle Grenade et Ecuador* (1886) p. 1-62. Berlin.

[31] W. O. Dietrich: *op. cit.*, p. 183-185.

[32] A. Silvestri: *Revisione di Orbitoline Nordamericane*, Pont. Accad. Sci., Mem., vol. 16 (1932) p. 375; *Foraminiferi del Cretaceo della Somali*, Paleont. Italica, vol. 32 (1932) *Paleontologia della Somalia: Fossili del Cretaceo*, p. 177.

[33] T. W. Vaughan: *op. cit.*

(Karsten) may be a synonym of *O. tezana*. In 1926 Mrs. Hodson[34] described *O. texana* (Roemer), *O. texana* var. *asaguana* Hodson, *O. texana* var. *monagasa* Hodson, and *O. thompsoni* Hodson from Rio Asagua, State of Monagas, Venezuela (probably El Cantil formation). Vaughan[35] states that these are all growth forms of *O. texana* (Roemer) and further mentions specimens of *Orbitolina* from Guatemala and from three localities in Venezuela (Toas Island, State of Zulia; southwest of Valera, State of Trujillo; and 0.8 kilometer southwest of Bergantin, State of Anzoategui) which he considers as belonging to this same species. The last mentioned Venezuelan collection is undoubtedly from the Bergantin beds.

The writer has compared specimens from the Glen Rose formation with those from the Bergantin beds. There is considerable individual variation in both Venezuelan and Texan material but there seems to be little basis for specific differentiation. Taking into consideration the conclusions of Vaughan and of Silvestri, it seems probable that all the American occurrences of *Orbitolina* including those of the Bergantin beds belong to a single species and that this is the species so characteristic of the Glen Rose formation of Texas. With regard to nomenclature, the writer follows Silvestri in calling the species for the present *O. concava* (Lamarck) var. *texana* (Roemer), although the variety name seems to have little more than geographic significance.

In Europe *O. concava* (Lamarck) has been considered particularly characteristic of the Cenomanian, according to Silvestri,[36] although it is known as early as the Aptian. However, Silvestri considers it indistinguishable from *O. subconcava*, which is common in the Aptian and Albian. The occurrence of the species in the Glen Rose formation is thus in accord with the supposed European range since the Glen Rose is believed to be equivalent to upper Aptian or lower Albian.[37] Some of the limestones in the lower part of the section are almost entirely composed of the tests of this foraminifer; on the weathered surface of the rock, they are readily visible to the naked eye. The *Orbitolina* limestones of the Bergantin beds are probably of upper Aptian or lower Albian age and approximate time equivalents of the Glen Rose formation of Texas.

Some of the Bergantin limestones contain many molluscan fossils but these are usually recrystallized and almost impossible to extract from the rock. Dietrich[38] identified the following forms from the material collected by Karsten from these beds: *Exogyra Minos* Coq., *Exogyra* sp., *Cucullaea* sp., *Venus* sp., *Pholadomya* sp., *Natica* sp., *Turritella* sp. He regarded these beds as Urgonian (Barremian-Aptian). However, he also mentions a specimen of *Enallaster* aff. *texanus* Roemer from Bergantin which he considers indicative of Vraconian (Lower Cenomanian) age. Numerous species have been identified from the time equivalent El Cantil formation in other parts of northeastern Venezuela. In 1922 Collet[39] examined ammonites from a collection made by Reinhard[40] near Aragua de Maturin, State of Monagas, and identified them as representing without doubt lower and upper Aptian. Gregory[41]

[34] H. K. Hodson: *Foraminifera from Venezuela and Trinidad*, Am. Paleont., Bull., vol. 12, no. 47 (1926) p. 4-6.

[35] T. W. Vaughan: *op. cit.*, p. 610.

[36] A. Silvestri: *op. cit.*, p. 375; *op. cit.*, p. 174.

[37] W. S. Adkins: *Handbook of Texas Cretaceous fossils*, Univ. Texas Bull., no. 2838 (1928) p. 7.

[38] W. O. Dietrich: *op. cit.*, p. 183, 185.

[39] L. W. Collet: *Sur la présence au Venezuela d'Aptien à faune mediterraneo-alpine*, Soc. Phys. Hist. Nat. Genève, C. R., vol. 39, no. 1 (1922) p. 16-17.

[40] M. Reinhard: *Géologie de la région orientale du Venezuela*, Soc. Phys. Hist. Nat. Genève, C. R., vol. 39, no. 1 (1922) p. 15.

[41] J. W. Gregory: *Some Lower Cretaceous corals from eastern Venezuela*, Geol. Mag., vol. 64 (1927) p. 440-444.

worked on corals from Punceres, State of Monagas (probably El Cantil formation), and concluded they were of Urgonian age. Liddle[43] gives the El Cantil formation an Aptian and Albian age "correlating with the Fredericksburg and Washita divisions of southwestern United States", and mentions numerous fossil species. Dietrich[45] mentions numerous species from the Karsten collections of El Cantil limestone and considers them largely indicative of Aptian age. While further work is needed, it seems justifiable for the present to consider the Bergantin beds as Middle Cretaceous and largely of Aptian-Albian age. Maury,[44] however, has considered them probably Cenomanian and it is certainly possible that the uppermost part may be of this age.

Stratigraphic Relations: Because of the lack of adequate exposures nothing can be said regarding the relation of the Bergantin beds to either overlying or subjacent formations in the Rio Querecual section. Elsewhere there seems to be a gradational contact between El Cantil formation and the underlying Barranquin formation and the writer knows of no evidence for an unconformity between the El Cantil and the overlying Guayuta group although the distinct lithologic difference may be suggestive of a break of some sort.

Correlation: Limestones in the Bergantin beds apparently thicken eastward, and in Monagas and much of Sucre the time equivalent of these beds is the El Cantil formation which, according to Liddle,[45] is about 75 per cent limestone. As previously mentioned, the Aptian-Albian age of the bulk of the El Cantil formation seems fairly well established.

The El Cantil stage is represented in western Venezuela by the Capacho limestone of Tachira[46] and the Cogollo limestone of the Perija mountain front[47] and the Venezuelan Andes.[48] In Colombia it includes at least a part of the Villeta limestone.[49] In Trinidad isolated occurrences of Middle Cretaceous limestone are known at Pointe-a-Pierre, Plum Creek, Mount Harris, the Nariva River, and elsewhere. Fossils have been described from these localities by Guppy, Bullen-Newton, Sommermeier, Harris and Hodson, and others.[50]

Distinguishing Features: The Bergantin beds include more limestone and less sandstone than the underlying Barranquin formation, and glauconite is more common. The Bergantin limestones are usually lighter colored and more massive than those of the overlying Querecual formation, and differ markedly in thin-section character (Pl. 4). Glauconite is absent or very rare in the Querecual formation but is common in the Bergantin beds. The pelagic Foraminifera, so abundant in the Querecual limestones, are lacking in the Bergantin limestones. *Orbitolina* is common in the Bergantin limestones but unknown in the Querecual formation. Gritty feldspathic sand-

[43] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928) p. 126. J. P. MacGowan, Fort Worth, Texas.

[45] W. O. Dietrich: *Zur Paläontologie und Stratigraphie der Kreide und des Tertiars in der ostkaribischen Kordillere Venezuelas*, Centralbl. Mineral., Geol., Paläont., no. 6 (1924) p. 183-185.

[44] C. J. Maury: *Venezuelan stratigraphy*, Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 413.

[45] R. A. Liddle: *op. cit.*, p. 125.

[46] W. Sievers: *Die Cordillere von Merida nebst Bemerkungen uber die Karibische Gebirge*, Penk. Geogr. Abh., vol. 3, no. 1 (1888) 238 pages.

[47] H. D. Hedberg: *op. cit.*, p. 229-246.

[48] Rolf Engleman: *Geology of Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 19 (1935) p. 769-792.

[49] F. M. Anderson: *Original source of oil in Colombia*, Am. Assoc. Petrol. Geol., Bull., vol. 10, no. 4 (1926) p. 384.

W. O. Dietrich: *Zur Stratigraphie der kolumbianischen Ostkordillere*, Zentralbl. Mineral., Geol., Paläont., Abt. B, no. 3 (1935) p. 75.

[50] E. Lehner: *Introduction à la géologie de Trinidad et bibliographie géologique*, Annales de l'Office nationale des combustibles liquides, no. 4 (1935) p. 691-730.

stones occur in both Barranquin formation and Bergantin beds but are lacking in the Querecual formation.

The Bergantin beds are very similar to the time equivalent El Cantil formation farther east but are distinguished from that formation by a lesser proportion of limestone and an increased prominence of glauconite and sandstone and shale.

QUERECUAL FORMATION (GUAYUTA GROUP)

(Plate 9, section A)

NAME AND TYPE LOCALITY: The type section of this formation is on the Rio Querecual southeast of the town of Bergantin, from a point about 250 meters upstream from Paso Hediondo to a point about 600 meters downstream from Paso Hediondo.

The existence of a distinctive and remarkably uniform Upper Cretaceous unit of black carbonaceous limestone and black calcareous shale throughout much of northern South America is well established. Garner[51] in 1926 proposed the name Guanoco shale for this unit in northeastern Venezuela but gave only a very brief and rather indefinite indication of its scope and character. In 1928 Liddle[52] introduced the term Guayuta formation with the Rio Guayuta in the State of Monagas as type, and this name has come into common use. Unfortunately, however, Liddle failed to designate definite limits to the formation in his type section so that it is impossible to extend the name to the Rio Querecual with any assurance that it is being used with exactly the same significance given to it by Liddle or by other geologists. Liddle designated the section on Rio Guayuta northeast of Cerro Aragua as the type of his Guayuta formation and evidently considered the black carbonaceous limestone and black calcareous shale as its principal lithologic feature. No upper limit of the formation and geographic limits are given, and Liddle states that "the upper 400 feet are composed of brownish gray arenaceous concretionary shale"[53] while the basal part of the overlying Aragua formation in this same locality consists of "200 feet of arenaceous shale"![54] The angular unconformity which Liddle believes to separate the two formations is no longer generally recognized.

Likewise, Liddle mentions nothing concerning the lower limit of his Guayuta formation in the type section and it is the writer's understanding that it is here separated from the underlying El Cantil formation by a major fault. Liddle leads us to infer that the total thickness of continuous section on Rio Guayuta does not exceed 1500 feet and since he states that the formation in northeastern Venezuela averages from 3000 to 3500 feet in thickness it would seem that on the Rio Guayuta much of the basal portion of the unit is cut out by this fault. Since accurate definition of formations is essential to their use in correlation and since the Upper Cretaceous sediments are better and more completely exposed on Rio Querecual than on Rio Guayuta, the name Querecual formation is here proposed for this black limestone and shale formation of northeastern Venezuela, with the Rio Querecual section as type. Because the term "Guayuta" has had rather wide usage it is retained in a broader sense as a group term to include both the Querecual and San Antonio formations as defined in this paper.

LITHOLOGY: The Querecual formation is very homogeneous and consists almost entirely of hard, black, thin-bedded, and laminated carbonaceous limestone and black,

[51] A. H. Garner: *Suggested nomenclature and correlation of the geological formations in Venezuela*, Am. Inst. Min. Metall. Eng., Tr. (April 1926) p. 679.
[52] R. A. Liddle: *op. cit.*, p. 154-156.
[53] *Op. cit.*, p. 156.
[54] *Op. cit.*, p. 222.

very calcareous shale (Pl. 3, fig. 1). Particularly characteristic are discoidal, spheroidal, and ellipsoidal limestone concretions ranging from a few inches to several feet in diameter.

The laminated character of the Querecual limestone is particularly striking in the lower half of the formation. This lamination is very regular and is apparently due to a fine alternation in the relative proportions of calcium carbonate and carbonaceous matter. There are frequently 15 to 20 laminae to the inch (Pl. 3, fig. 3). The upper portion of the formation is less finely laminated than the lower and there are many beds as much as a foot thick without lamination. Black cherty limestone is also common in the upper part of the formation and there are occasional seams of black chert entirely free from calcium carbonate.

The characteristic limestone concretions are found throughout the greater part of the formation. They vary with different horizons from the size of a hen's egg to large lenticular masses with thicknesses of several feet which may perhaps be considered lenses or incipient beds rather than concretions. The separation of the concretions from their matrix seems to be due largely to increased concentration of calcium carbonate. There is no apparent difference in color but the concretions are harder than the surrounding rock. The laminae to some extent bend around the concretions both above and below, but also in part pass through or die out within them (Pl. 3, fig. 2). Some of the concretions are highly pyritic and some contain fossil shells as nuclei.

The rock of the Querecual formation is frequently referred to as "black shale". However, because of the hardness and high calcium carbonate content the writer prefers to call the bulk of the formation limestone. Calcareous shales do occur at some horizons, however.

Thin-section study of the Querecual limestones shows them to be almost identical in microscopic character with the time equivalent La Luna limestone of western Venezuela. Many of them are in large part made up of the tests of pelagic Foraminifera (*Globigerina, Gümbelina,* etc.), set in a matrix of black calcareous-carbonaceous matter (Pl. 4, figs. 3 and 4). The foraminiferal tests are usually filled with clear calcite and the fine lamination is frequently due to alternating concentration of foraminiferal tests and carbonaceous matter along bedding planes. The appearance of the slides is identical with that of slides from the La Luna formation which have been figured in a previous publication.[55]

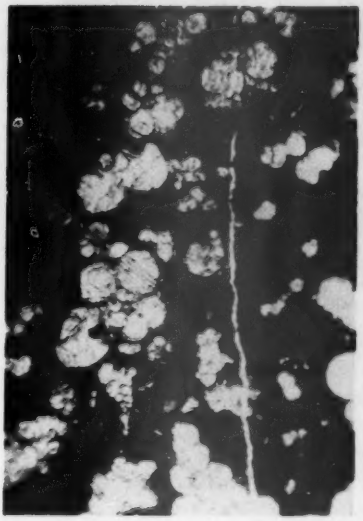
Formation Boundaries: The base of the Querecual formation is at least as low in the Rio Querecual section as the first occurrence of typical black thin-bedded or laminated carbonaceous limestone. However, the exact contact with the underlying Bergantin beds is not exposed and lies within a covered interval several hundred feet thick.

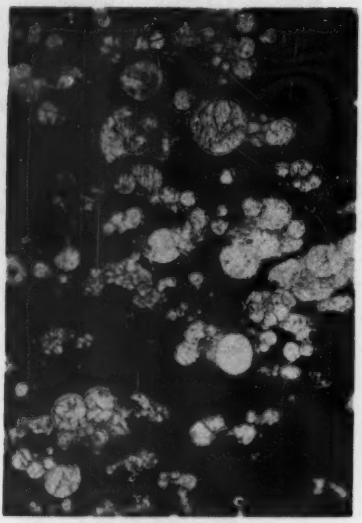
The top of the formation is placed at the base of the first more or less continuous sandstone bed above the typical development of carbonaceous limestone and shale. On the Rio Querecual this is a very easily recognized contact as the basal sandstone of the overlying San Antonio formation is prominent and about 30 feet thick. In other sections it may be less marked due to the appearance of thin sandstone lenses in the uppermost part of the Querecual formation.

Thickness: The thickness of the formation measured on the Rio Querecual is 2420 feet. The section is in general regular although there is some indication of faulting near the base. The exact contact with the underlying Bergantin beds is not exposed.

[55] H. D. Hedberg: *Cretaceous limestone as petroleum source rock in northwestern Venezuela,* Am. Assoc. Petrol., Geol., Bull., vol. 15, no. 3 (1931) p. 229-246.

FIGURES 1 AND 2. *Orbitoline concava* (LAMARCK) VAR. *texana* (ROEMER)
From Bergantin beds on Rio Querecual. X16





FIGURES 3 AND 4. THIN-SECTIONS OF QUERECUAL LIMESTONE
Showing by transmitted light the calcite-filled tests of pelagic Foraminifera (*Globigerina, Gümbelina*) in black carbonaceous matrix. X50

THIN-SECTIONS OF CRETACEOUS LIMESTONES

FIGURE 1. MASSIVE SANDSTONE OF SAN JUAN MEMBER OF SANTA ANITA FORMATION
On Rio Querecual near Paso Santa Anita.

FIGURE 2. LOWER MEMBER OF CARAPITA FORMATION
Typical brownish-greenish gray, massive but laminated, fine-grained sandstone; on Quebrada Carapita.

FIGURE 3. DARK-GRAY FISSILE FORAMINIFERAL SHALE
Middle part of Carapita formation on Quebrada Carapita.

MINERALOGY: The formation carries much pyrite, and hydrogen sulphide springs are common in its outcrop belt. No glauconite has been noted. The formation on the Rio Querecual contains little clastic material for the determination of heavy detrital minerals but sandstone lenses in the upper part of the formation elsewhere show a simple zircon-leucoxene suite.

PALEONTOLOGY, AGE, AND CORRELATION: Large fossils are scarce in the type section and those collected by the writer are limited to fragments of ammonites, *Inoceramus* sp., and other mollusks occasionally found within the limestone concretions. Foraminifera are abundant. *Globigerina* predominates, but *Gümbelina* and *Globotruncana* have also been identified.

The Querecual formation is exposed in numerous river sections in northeastern Venezuela, and, as previously mentioned, is approximately synonymous with Liddle's Guayuta formation and Garner's Guanoco shale. On Rio Guayuta Liddle[56] has noted the presence of *Inoceramus cripsi* Mantell. Specimens of *Inoceramus* collected by Karsten from Cocollar (=Cocoyal ?), State of Sucre, are probably from strata of Querecual age. These have been identified by Heinz[57] as *Inoceramus vancouverensis* Shum. mutation *schondorfi* Heinz and *Inoceramus* sp. (? ex. aff. *cripsi* Mantell) and are believed by him to be indicative of Cenomanian age. Maury[58] and Dietrich[59] have identified *Inoceramus labiatus* Schlotheim also from beds in northeastern Venezuela believed to be equivalent to the Querecual formation (called Hurupu beds by Maury[60]). Thus, available paleontologic data from northeastern Venezuela suggest that the formation is of Cenomanian-Turonian age.

The black shaly limestones and calcareous shales of the Querecual formation belong to one of the most widespread stratigraphic units in northern South America. In western Venezuela this is known as the La Luna limestone in the Sierra de Perija[61] and in the Venezuelan Andes.[62] In eastern Colombia it is included in the Palmira series of Wheeler[63] and is probably the uppermost part of Hettner's Villeta formation. It is probably also the upper part of the Napo limestone of Ecuador.[64] Fossils from the La Luna and Tachira formations have been discussed by Liddle,[65] Gerhardt,[66] Karsten,[67] and others. Those from the unit in Colombia have been described by

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[56] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928). J. P. MacGowan, Fort Worth, Texas.

[57] R. Heinz: *Uber die Oberkreide-Inoceramen Sud-Amerikas und ihre Beziehungen zu denen Europas und anderer Gebiete*, Mitt. Min.-Geol., Staatsinst. Hamburg, vol. 10 (1928) p. 41-97.

[58] C. J. Maury: *A contribution to the paleontology of Trinidad*, Philadelphia Acad. Nat. Sci., Jour., 2d ser., vol. 15 (1912) p. 23-112; *Venezuelan stratigraphy*, Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 411-414.

[59] W. O. Dietrich: *Zur Palaontologie und stratigraphie der Kreide und des Tertiars in der ostkaribischen Kordillere Venezuelas*, Zentralbl. Mineral., Geol., Paläont., no. 6 (1924) p. 181-187.

[60] C. J. Maury: *Venezuelan stratigraphy*, Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 411-414.

[61] A. H. Garner: *op. cit.*
H. D. Hedberg: *op. cit.*

[62] Rolf Engelman: *op. cit.*

[63] O. C. Wheeler: *Tertiary stratigraphy of the middle Magdalena Valley*, in H. A. Pilsbry and A. A. Olsson: *Tertiary fresh-water mollusks of the Magdalena embayment, Colombia*, Philadelphia Acad. Nat. Sci., Jour., vol. 87 (1935) p. 21-39.

[64] T. Wasson and J. H. Sinclair: *Geological explorations east of the Andes in Ecuador*, Am. Assoc. Petrol. Geol., Bull., vol. 11, no. 12 (1927) p. 1253-1281.

[65] R. A. Liddle: *op. cit.*

[66] K. Gerhardt: *Beitrag zur Kenntnis der Kreideformation in Columbien*, Neues Jahrb. Mineral., Geol., Paläont., Beil.-Bd. 11 (1897) p. 118-208.

[67] H. Karsten: *Uber die geognostische verhaltnisse der westlichen Columbien, der heutigen Republiken Neu-Grenada und Equador*, Amtlicher Bericht 32 Versammlung deutsch. Naturforsch. und Arzte zu Wien (1858) p. 80-117.

Karsten,[68] Anderson,[69] Dietrich,[70] and others. They seem to be largely of Turonian age and show close affinity to those of the Eagle Ford formation of Texas.

STRATIGRAPHIC RELATIONS: No conclusions can be reached on the stratigraphic relations between the Querecual formation and the underlying Bergantin beds in the Rio Querecual section because of lack of exposures at the contact. Elsewhere the two appear to be conformable although the change in lithologic character is marked.

The Querecual formation grades upward conformably into the San Antonio formation.

DISTINGUISHING FEATURES: The formation is distinguished by its characteristic lithology—thin-bedded and laminated, black, carbonaceous limestone and black calcareous shale; by the common presence of discoidal, spheroidal, and ellipsoidal limestone concretions; and by the abundance of pelagic Foraminifera in the limestones. It is related to the overlying San Antonio formation which contains similar limestones and shales but is differentiated from that formation by the absence of laterally continuous sandstones.

SAN ANTONIO FORMATION (GUAYUTA GROUP)

(Plate 9, section A)

NAME AND TYPE LOCALITY: The formation is named from Cerro San Antonio just north of the town of Bergantin. It is prominently exposed near the crest of this hill, but the type section is here designated as that on Rio Querecual south of Bergantin from the base of the first sandstone downstream from Paso Hediondo (about 600 meters from the Paso) to the base of the thick gorge-forming sandstone about 150 meters upstream from Paso Santa Anita. Unfortunately, there are no locality names in the type section so it has been necessary to choose a formation name from a slightly different locality. The San Antonio and Querecual formations together make up the Guayuta group.

LITHOLOGY: The formation consists of hard- thin-bedded, black, carbonaceous limestone and calcareous shale similar to that of the underlying Querecual formation but alternating with beds of hard, light-gray, calcareous sandstone from 1 to 30 feet thick. Thin sections of the limestone frequently show abundant tests of pelagic Foraminifera, but these are usually filled with carbonaceous matter instead of with calcite as in the Querecual formation. Lenticular limestone concretions ranging from a few inches to several feet in diameter are common. Both limestone and shale are frequently sandy and some of the limestone is distinctly cherty. On Cerro San Antonio at certain horizons there are sharp lateral variations between dark shales or limestones and a buff, porous, siliceous rock with numerous foraminiferal molds. Engleman[71] has attributed similar color changes in the La Luna formation of the Venezuelan Andes to fading and leaching.

Sandstones make up less than a third of the total thickness of the formation. They are well sorted, medium-grained, and almost always have calcareous cement. The sandstone beds are extremely variable in thickness, and thicken and thin at the expense of the adjacent shale or limestone with which they are in sharp contact.

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[68] *Ibid.*

[69] F. M. Anderson: *op. cit.*, p. 382-404.

[70] W. O. Dietrich: *Zur Stratigraphie der kolumbianischen Ostkordillere*, Zentralbl. Mineral., Geol., Paläont., Abt. B, no. 3 (1935) p. 74-82.

[71] Rolf Engelman: *Geology of Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 19 (1935) p. 780.

Sandstone dikes are a striking feature of the formation both in the river section and on the top of Cerro San Antonio (Pl. 6, fig. 1). They range in thickness from a few inches to 2 feet and cut across the limestones and shales at angles varying up to as much as 90 degrees to both bedding and strike. The dikes are frequently branching and may intersect at various angles. Little relation to jointing can be established. In one instance a dike several inches thick was found cutting directly through one of the characteristic limestone concretions of the formation. The sandstone of the dikes shows little or no stratification but is lithologically identical to that of the bedded sandstones although in no case where the dikes seem to be actually connected with the beds. With one exception, the heavy mineral character of the dikes was found to be identical with that of the bedded sandstones.

Formation Boundaries: The lower limit of the formation is placed at the base of the first more or less continuous sandstone above the typical development of the black carbonaceous limestones and black calcareous shales of the Querecual formation. On the Rio Querecual this contact is very distinct and the basal sandstone of the San Antonio formation is about 30 feet thick. In other sections it is less abrupt owing to the occurrence of thin sandstone lenses only a few feet in length in the uppermost part of the Querecual formation.

The top of the San Antonio formation is placed at the base of the very thick gorge-forming San Juan sandstone member of the Santa Anita formation. This is approximately the upper limit of the black carbonaceous and foraminiferal limestones although a few such beds occur above the San Juan sandstone.

In sections where the sandstones of the San Antonio formation are poorly developed with respect to the black limestones and shales, it may be difficult to separate this formation from the Querecual formation and, as already stated, the two may be combined conveniently under the broader term Guayuta group. On the other hand, with increasing development of sandstones in the San Antonio formation it becomes difficult to separate it from the overlying Santa Anita formation and in some areas it may be convenient to include it as a lower member of that formation.

Thickness: The formation is almost completely exposed on the Rio Querecual and both the base and top may be closely defined. Dips are almost vertical and strikes are regular so that the calculated thickness of 1290 feet for this formation is quite accurate.

Mineralogy: The sandstones of the San Antonio formation carry a simple zircon-leucoxene mineral suite. The average distribution of minerals is as follows: leucoxene—4, zircon—4, ilmenite—1, tourmaline—1, rutile—1, brookite (occasionally present). A single exception to this mineralogy is a sandstone dike (Sample S-2521) which shows a high ilmenite content and a few grains of staurolite.

Paleontology, Age, and Correlation: No large fossils were noted in this formation on the Rio Querecual. However, a collection given to the writer by Clemente De Juana from the lower part of the formation on Cerro San Antonio contains *Inoceramus* aff. *cripsi* Mantell, *Tunisites* sp., *Hoplites* sp., and *Acanthoceras* sp.—an assemblage indicative of an age at least as old as Turonian.

Thin sections of the San Antonio formation limestones, like those of the Querecual formation, frequently show numerous pelagic Foraminifera. However, in the San Antonio formation, these are usually associated with a considerable proportion of benthonic forms. The calcareous shales of the San Antonio formation also yield some poorly preserved benthonic Foraminifera and the buff porous claystones seen on Cerro San Antonio contain numerous foraminiferal casts. Particularly charac-

teristic of the formation are *Siphogenerinoides ewaldi* (Karsten)[73] and *Nodosaria* sp. These are well preserved in the limestones but can usually be recovered from the shales only as detached segments. There are a few other species suggestive of the Colon shale of western Venezuela.

The San Antonio formation is definitely of late Cretaceous age. From its close relation to the Querecual formation and from the molluscan fossils collected by de Juana it seems probable that in its lower part it is of Turonian age. On the other hand, the presence of *Siphogenerinoides ewaldi* (Karsten), which is widespread in the Colon and Guadalupe formations of western Venezuela and Colombia suggests that the formation is younger than the La Luna limestone of western Venezuela which has been rather definitely correlated with the Eagle Ford stage of Texas and the Turonian stage of Europe. The small foraminifera of the Colon shale indicate an approximate correlation with the Taylor stage of Texas (Senonian) and it is thus probable that the bulk of the San Antonio formation is of Senonian age.

The formation constitutes the upper part of the Guayuta formation of some workers in this region. It is probably equivalent in age to at least the lower part of the Colon shale of western Venezuela and to parts of the Umir and Guadalupe formations of eastern Colombia[75] and the San Fernando "argiline" or lower part of the Tarouba formation of Trinidad.[74]

Stratigraphic Relations: The San Antonio formation is conformable with the Querecual formation below and the Santa Anita formation above. It constitutes a transition zone between the typical lithology of these two formations.

Distinguishing Features: The formation is distinguished from all others except the Querecual formation by its hard black carbonaceous and foraminiferal limestones. It is distinguished from the Querecual formation by the presence of numerous sandstones and by a larger proportion of benthonic Foraminifera in its limestones.

SANTA ANITA FORMATION

(Plate 9, section B)

Name and Type Locality: This formation is named from Paso Santa Anita, the second crossing of the Rio Querecual south from Bergantin along the Barcelona road. The neighborhood about this crossing is also known as Santa Anita. The type section on the Rio Querecual extends from the base of the gorge-forming sandstone about 150 meters upstream from Paso Santa Anita to the base of the thick, light-colored, quartzitic sandstone of the Merecure formation which forms a gorge and waterfalls about 600 meters downstream from Paso Santa Anita and just below the mouth of Quebrada de las Caratas. The formation includes two members: a lower

[73] *Orthocerina ewaldi* Karsten, Amtlicher Bericht 32 Versammlung deutsch. Naturforsch. und Arste zu Wien (1858) p. 114, pl. 6, figs. 3 a-c. Cretaceous of Tocayma, Colombia.

Siphogenerinoides ewaldi (Karsten), Cushman, Contrib. Cushman. Lab. Foram. Res. (1929) vol. 5, no. 3, p. 58—Cushman and Hedberg, Contrib. Cushman Lab. Foram. Res. (1930) vol. 6, pt. 3, p. 68, pl. 9, figs. 10-12. Lower part of Colon shale (Upper Cretaceous) of District of Escuque, State of Trujillo, Venezuela.

Orthokarstenia ewaldi (Karsten), Dietrich, Zentralbl. Mineral., Geol., Paläont., Abt. B, no. 3 (1935) p. 80, text figs. 1-3. Guadalupe formation (Upper Cretaceous) of Colombia.

[74] O. C. Wheeler: *Tertiary stratigraphy of the middle Magdalena Valley*, in H. A. Pilsbry and A. A. Olsson: *Tertiary fresh-water mollusks of the Magdalena embayment, Colombia*, Philadelphia Acad. Nat. Sci., Jour., vol. 87 (1935) p. 21-39. Personal communication from Mr. Wheeler (August 20, 1935) states that the age of the Umir formation, considered as probably Eocene in the above publication, has since been determined as Upper Cretaceous.

W. O. Dietrich: *Zur Stratigraphie der kolumbianishcen Ostkordillere*, Zentralbl. Mineral., Geol., Paläont., Abt. B, no. 3 (1935) p. 74-82.

[75] H. G. Kugler: *Summary digest of geology of Trinidad*, Am. Assoc. Petrol. Geol., Bull., vol. 20 (1936) p. 1442.

San Juan sandstone member and an upper Caratas member. The formation name was suggested by Clemente de Juana.

LITHOLOGY: From the mouth of Quebrada San Juan near Paso Santa Anita to a point about 150 meters upstream from the Paso, the Rio Querecual flows through a sandstone gorge formed by the basal San Juan sandstone member of the Santa Anita formation (Pl. 5, fig. 1). The member is 320 feet thick and consists entirely of very hard, gray to light-gray, fine- to medium-grained, well-sorted sandstone in beds usually from 1 to 3 feet in thickness. The rock is sparingly glauconitic and is calcareous in its uppermost part. It weathers to a pinkish gray.

The upper Caratas member of the Santa Anita formation extends from Paso Santa Anita to the top of the formation, about 600 meters downstream from the Paso and just below the mouth of Quebrada de las Caratas. The sediments of this unit are dominantly gray in color, fine-grained, almost always more or less glauconitic, and frequently calcareous or dolomitic. They consist in general of gray and brownish-gray glauconitic and calcareous shales and sandy shales, very hard gray, fine- to medium-grained, glauconitic sandstone, and very hard gray or bluish-gray, dolomitic and calcareous, argillaceous siltstones and impure dolomites and limestones.

At the base of the Caratas member, immediately above the San Juan sandstone, is 50 to 100 feet of black calcareous shale somewhat similar to that of the San Antonio formation and similarly cut by sandstone dikes. This is overlain by an 800-foot covered interval on the river which is only in small part filled in by a few outcrops of brownish-gray foraminiferal shale and buff, porous, highly foraminiferal claystone in tributary quebradas and along the old trail on the east side of the river. This part of the member is probably dominantly shale.

From 900 to 1100 feet above the base of the member is a well-exposed interval of hard gray argillaceous and silty dolomite, calcareous and dolomitic siltstones, and argillaceous limestone. There is a minor amount of hard calcareous sandstone and sandy shale. Glauconite is present in most of these sediments, and some of the sandstones and sandy shales are highly glauconitic. The dolomitic character is the distinctive feature of the interval. The dolomitic rocks are very hard and dense, and are dark gray in color. They are difficult to name in the field, but in thin section some are seen to be made up almost entirely of clear dolomite rhombs in an interstitial matrix of gray, silty, argillaceous or siliceous matter; others are composed dominantly of quartz silt in a dolomitic and calcareous argillaceous matrix.[75] Many of the samples show Foraminifera, largely of pelagic types (*Globigerina*), but other fossils have not been observed. In some, the *Globigerina* tests appear to be largely filled with siliceous matter.

Above these dolomitic sediments is a 200-foot covered interval to the base of a massive to thick-bedded, very hard, fine-grained to medium-grained, well-sorted sandstone which occupies the interval from 1330 to 1460 feet above the base of the Caratas member. This sandstone forms a small gorge in the river and its appearance is almost identical with that of the San Juan sandstone. It is slightly glauconitic throughout and in its upper part has a greenish-gray cast, owing to the abundance of glauconite pellets.

About 80 feet above the top of the glauconitic sandstone is the beginning of a 170-foot interval of very hard, dark bluish-gray, calcareous, dolomitic, and glauconitic fine-grained sandstone and siltstone with some brownish gray shaly siltstone (1530-

[75] The writer is indebted to James D. Hedberg for data on the chemical composition of two samples in this dolomitic interval. Sample S-2529 was 43.44% soluble in hot HCl and showed 12.80% CaO, 7.69% MgO, and 2.28% Fe_2O_3. Sample S-2543 was 27.36% soluble in hot HCl and showed 8.16% CaO, 1.88% MgO, and 2.50% Fe_2O_3.

1700 feet above the base of the Caratas member). This very hard rock weathers characteristically to rounded surfaces from which it is exceedingly difficult to break specimens (Plate 7, fig. 1). The next 100 feet of section is covered but the uppermost 250 feet of the member (1800-2050 feet above the base) is well exposed. It consists largely of very hard, brownish-gray and bluish-gray, calcareous and glauconitic siltstone and fine-grained sandstone like that already mentioned, with some brownish-gray silty shale and two thin intervals of glauconitic and limonitic pebbly grit. At the top is a light-gray calcareous shale with thin, closely spaced seams of hard, nodular, argillaceous, limestone concretions a few inches in diameter. Above the shales and in immediate contact with the overlying Merecure formation is a 2-foot bed of relatively soft, yellowish, argillaceous, fine-grained sandstone, coated with melanterite at the surface (Plate 7, fig. 2).

Formation Boundaries: The lower boundary of the Santa Anita formation is placed at the base of the huge San Juan sandstone which through its effect on topography constitutes a distinct mappable horizon along much of the mountain front. This sandstone in the Rio Querecual section is many times thicker than any of the sandstones of the San Antonio formation.

The top of the formation is placed at the base of the thick interval of massive, light-colored, quartzitic sandstones which form the first prominent ridge above the San Juan sandstone. This marks the upper limit of the characteristic, dirty brownish-gray, glauconitic shales and blue-gray limestones, dolomites, and calcareous siltstones of the Caratas member of the Santa Anita formation.

Thickness: The thickness of the Santa Anita formation measured on the Rio Querecual is 2370 feet. The San Juan sandstone member is 320 feet thick and the Caratas member is 2050 feet thick.

Mineralogy: The formation in general shows a simple zircon-leucoxene suite of heavy detrital minerals: ilmenite—1-2, leucoxene—3-4, zircon—4, tourmaline—1, rutile—1. Rare grains of garnet and staurolite have been found in the Caratas member. Authigenic and secondary minerals include glauconite, which is particularly characteristic of the formation, and dolomite, calcite, and pyrite. Some sandstones in this formation, as well as in other Cretaceous and Eocene formations of this section, carry a pale-yellow titanium-bearing mineral of tabular habit which resembles anatase in appearance but differs from this mineral in its very low birefringence. The sharp outlines and occasional well-preserved terminations of this mineral suggest that it is of secondary origin. It is pale yellow to yellowish brown, of adamantine luster, usually tabular though occasionally with pyramid terminations. The grains are small, squarish, usually less than 100 microns in diameter and about a third as thick, and show sharp edges and corners. Cleavage seems to be developed in two or three directions at right angles to each other so that the grains show characteristic blocky outlines.

Optical properties as far as could be determined are as follows: refractive index high, probably 2.00 or more. Birefringence low, less than .010. Grains are usually clouded or semi-opaque so that interference colors are spotty. Non-pleochroic. Optical character negative; sometimes apparently uniaxial, in other grains definitely biaxial with a small optic axial angle. Birefringence is so low that colors in fields showing interference figures do not rise above a pale yellow of the first order.

Paleontology and Age: In the type section, the San Juan sandstone member of the Santa Anita formation is apparently barren of fossils. In the Caratas member no megascopic fossils were noticed, but Foraminifera are fairly common. Detailed study of these has not yet been completed, and only a few preliminary observations can be offered at this time.

The dark shales immediately above the San Juan sandstone and at the base of the Caratas member (Samples S-2527A and S-2528) carry a number of poorly preserved Foraminifera which include:

Siphogenerinoides bramletti Cushman
Ventilabrella carseyae Plummer
Gümbelina sp.
Loxostomum plaitum (Carsey)

The evidence for Cretaceous age seems fairly definite.

Shales in the interval from 500 to 1100 feet above the base of the Caratas member carry a fairly abundant and varied fauna of poorly preserved Foraminifera. The affinities of this assemblage are clearly with either the uppermost Cretaceous or the Paleocene. A number of species are present which are common to the Lizard Springs shale of Trinidad which Cushman and Jarvis [76] have compared with the Velasco stage of Mexico. The names applied by Cushman and Jarvis are as follows:

Clavulina aspera Cushman var. *whitei* Cushman and Jarvis
Cribrostomoides trinitatensis Cushman and Jarvis
Cyclammina elegans Cushman and Jarvis
Gaudryina laevigata Franke var. *pyramidata* Cushman
Gaudryina oxycona Reuss
Gaudryina retusa Cushman
Globorotalia velascoensis (Cushman)
Globotruncana arca (Cushman)
Marginulina decorata (Reuss)
Marginulina trilobata d'Orbigny
Nodosaria limbata d'Orbigny var. *basiornata* Cushman and Jarvis
Nodosaria paupercula Reuss
Pulvinulinella velascoensis (Cushman)

These species are indeed largely suggestive of Cretaceous age and Thalmann [77] considers *Globotruncana* as a Cretaceous index genus. On the other hand, the assemblage also appears to be closely related to that of the Midway stage of Texas as described by Plummer.[78] The Midway is generally assigned to the Paleocene, although Scott [79] has recently considered it uppermost Cretaceous (Danian).

The dolomites, dolomitic siltstones, and limestones in this same interval carry Foraminifera which are largely pelagic (*Globigerina, Globotruncana*). They also show numerous white *Orbulina*-like spheres which may or may not be of organic origin.

Several samples in the upper part of the Caratas member show some poorly preserved Foraminifera but few of these are even generically identifiable and they contribute little information with respect to the age of the inclosing rocks. However, about 45 kilometers southeast of Santa Ines near the town of Urica, sandstones, probably belonging to the Santa Anita formation, form the prominent Cerro Corazon

[76] J. A. Cushman and P. W. Jarvis: *Upper Cretaceous Foraminifera from Trinidad*, U. S. Nat. Mus., Pr., vol. 80, art. 14, no. 2914 (1932) 60 pages.

[77] H. E. Thalmann: *Die regional-stratigraphische Verbreitung der oberkreta zischen Foraminiferan-Gattung Globotruncana Cushman, 1927*, Eclogae geol. Helv., Bd. 27, no. 2 (1934) p. 413-428.

[78] H. J. Plummer: *Foraminifera of the Midway formation in Texas*, Univ. Texas Bull., no. 2644 (1926) 206 pages.

[79] Gayle Scott: *Age of the Midway group*, Geol. Soc. Am., Bull., vol. 45 (1934) p. 1111-1158, pls. 132-134.

and on the south flank of this hill a glauconitic limestone is exposed which is believed to be in the upper part of the Caratas member. This limestone carries numerous specimens of a *Venericardia* of the *"planicosta"* group. These have been studied by R. Rutsch[80] of Basel who has concluded that they are probably identical with those of the Marac Quarry in Trinidad which he has identified as *V. parinensis* Olsson. He considers this species indicative of Paleocene age. Maury[81] believes the Soldado Rock and Trinidad beds carrying this same *Venericardia* are of Midway age.

Reviewing the evidence for the age of the Santa Anita formation, it seems that the San Juan sandstone member and the basal part of the Caratas member are definitely of Upper Cretaceous age. The middle portion of the Caratas member is probably of uppermost Cretaceous age but may be Paleocene. No direct criteria are available on the age of the upper part of the Caratas member, but the lithologic character and Foraminifera suggest that it is closely related in age to the middle part of the member while the probable correlation with the Cerro Corazon *Venericardia* horizon suggests a Paleocene age. It seems probable that the Santa Anita formation represents a transition between Cretaceous and Tertiary time. The often repeated statement that uppermost Cretaceous is lacking in Venezuela[82] will probably have to be revised.

CORRELATION: The San Juan member and other sandstones in the Santa Anita formation make prominent topography along much of the south border of the Serrania del Interior in northeastern Venezuela. The formation is undoubtedly included in the Aragua sandstone of Garner,[83] Liddle,[84] and others, but this name, while in common use, is not clearly defined and has been used to cover almost all sandstones overlying the Querecual formation in this region. Because of the lack of a specifically limited type section and because of the rather vague connotation the name has acquired, it is believed desirable to retain it only as a general group term to include San Antonio, Santa Anita, and Merecure formations where these are not readily differentiable.

Throughout much of the deeper portion of the Andean geosyncline of northern South America there was no break in deposition between Cretaceous and Tertiary time, and the interval near the boundary between those periods is represented in other regions by formations approximately equivalent to the Santa Anita formation.

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[80] R. Rutsch: *Beitrage zur Kenntnis tropisch-amerikanisher Tertiarmollusken, Part IV—Die stratigraphische Bedeutung der Venericardia planicosta und ihrer Verwandten,* Eclogae geol. Helv., vol. 29, no. 1 (1936) p. 152-186.

[81] C. J. Maury: *A contribution to the paleontology of Trinidad,* Philadelphia Acad. Nat. Sci., Jour., 2d ser., vol. 15 (1912) p. 23-112, pls. 5-13; *A new formational name (Soldado formation, Trinidad region),* Science, n. s., vol. 61 (1925) p. 43; *Venezuelan stratigraphy,* Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 411-414; *The Soldado rock type section of Eocene,* Jour. Geol., vol. 37, no. 2 (1929) p. 177-181.

[82] Henri de Cizancourt and M. D. Schneegans: *Introduction à la géologie du Venezuela et bibliographie géologique,* Annales de l'Office nationale de combustibles liquides, 11ième année, no. 1 (1936) p. 98.

R. A. Liddle: *Outlines of Venezuelan stratigraphy,* Pan-Am. Geol., vol. 57 (1932) p. 172.

A collection of ammonites from the Rio de Oro formation of eastern Colombia and western Venezuela (Quebrada del Rancho, Petrolea Structure, Santander del Norte, Colombia) was recently submitted to L. F. Spath, of the British Museum, for identification. A personal communication from him, dated February 18, 1937, states that the dominant ammonite genus in this material is *Sphenodiscus* and that there is no doubt about the Maestrichtian age of the fauna. This is probably the most definite paleontologic evidence available at present of the presence of late Cretaceous strata in northern South America and tends to substantiate the idea that there was no important break in deposition between Cretaceous and Tertiary strata in the geosynclinal basins of this region.

[83] A. H. Garner: *Suggested nomenclature and correlation of the geological formations in Venezuela,* Am. Inst. Min. Metall. Eng., Tr. (April 1926) p. 680.

[84] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928) p. 216. J. P. McGowan, Fort Worth, Texas.

In western Venezuela the time equivalents of the Santa Anita formation are the Upper Cretaceous Mita Juan formation and the Upper Cretaceous-Paleocene Rio de Oro and Guasare formations. In Colombia the Santa Anita formation is probably equivalent to the uppermost Umir and a part of the Lisama formation.[85] In Trinidad, the upper part of the Tarouba formation (Lizard Springs shale, Hobson's clay, "soft argiline") is to be correlated with the Caratas member of the Santa Anita formation. The *Venericardia planicosta* horizon of Cerro Corazon, which probably lies within or just above the upper part of the Caratas member, can be definitely correlated with similar *Venericardia* limestones in the Marac formation of Trinidad, with the Soldado formation[86] of Soldado Rock (between Venezuela and Trinidad), with the Toas Island limestone and the Guasare limestone of western Venezuela, with *Venericardia* limestones in northern Colombia, and perhaps with the Parinas formation of Peru.

STRATIGRAPHIC RELATIONS: Although there is a sharp lithologic change at the base of the formation there is no indication of unconformity with the underlying San Antonio formation. Further, there is no reason to believe in the presence of anything but local unconformities within the formation. Throughout the Caribbean region as a whole there seems to have been rather general emergence at the close of the Cretaceous and through Paleocene time and there is frequently a disconformity or even angular relation between the youngest known Cretaceous and the oldest known Tertiary deposits. However, within the troughs of the great Andean and Venezuelan geosynclines, the extensive subsidence during the Cretaceous continued into Eocene time so that Cretaceous-Tertiary transition formations are found and the exact division of the two systems becomes impossible. The writer agrees with Senn[87] that the oft-quoted angular unconformity of Jones and Whitehead[88] at Los Algodones in western Venezuela is not between Cretaceous and Tertiary strata but between Eocene and Miocene formations. In this connection, Engleman's[89] remarks concerning Cretaceous-Tertiary relations in the Venezuelan Andes are of interest. There is little if any change in dip or strike at the contact between the Santa Anita formation and the overlying Merecure formation but it is probable that at least an erosional unconformity intervenes between the two. There is a thin conglomerate at the base of the Merecure sandstone, and borings filled with pebbly sandstone extend down into the underlying Santa Anita formation. Furthermore, the lithologic character of the two formations is distinct and there is a hiatus between their supposed ages.

DISTINGUISHING FEATURES: The formation may be distinguished by the abundance of glauconite throughout; the presence of the thick San Juan sandstone at its base;

[85] O. C. Wheeler: *Tertiary stratigraphy of the middle Magdalena Valley*, in H. A. Pilsbry and A. A. Olsson: *Tertiary fresh-water mollusks of the Magdalena embayment, Colombia*, Philadelphia Acad. Nat. Sci., Jour., vol. 87 (1935) p. 27-28.

[86] C. J. Maury: *A new formational name (Soldado formation, Trinidad region)*, Science, n. s., vol. 61 (1925) p. 43; *Venezuelan stratigraphy*, Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 411-414; *The Soldado rock type section of Eocene*, Jour. Geol., vol. 37, no. 2 (1929) p. 177-181; *Bartonian and Ludian upper Eocene in the western hemisphere*, Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 375-376.

H. G. Kugler: *Das Eozänprofil von Soldado Rock bei Trinidad*, Eclogae geol. Helv., vol. 18, no. 2 (1923) p. 253-259.

[87] Alfred Senn: *Die stratigraphische Verbreitung der Tertiaren Orbitoiden mit spezieller Berucksichtigung ihres Vorkommens in Nord-Venezuela und Nord-Marokko*, Eclogae geol. Helv., vol. 28, no. 1 (1935) p. 79.

[88] W. F. Jones and W. L. Whitehead: *Cretaceous-Eocene unconformity of Venezuela*, Am. Assoc. Petrol. Geol., Bull., vol. 13, no. 6 (1929) p. 617-625.

[89] Rolf Engleman: *Geology of Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 19 (1935) p. 784.

the varied lithology which includes sandstones, siltstones, shales, limestones, and dolomites; the dense, bluish-gray, dolomitic siltstones and dolomites of the Caratas member; and the distinctive Foraminifera of this member.

In a sense the formation is unified by the variety of its lithology. Eventually, it may be desirable to raise the two members to formation rank, but this has not been done because of the similarity of sandstones in the Caratas member to those of the San Juan member, the only difference being one of thickness.

MERECURE FORMATION

(Plate 9, section B)

NAME AND TYPE LOCALITY: The formation is named from Quebrada Merecure which enters the Rio Querecual from the east about 2 kilometers north of Capaya. The outcrop belt on the Rio Querecual extends from the base of the light-colored quartzitic sandstone which forms a gorge and waterfalls about 600 meters downstream from Paso Santa Anita to a point about 400 meters downstream from the mouth of Quebrada la Haciendita. Only the lower part of the formation is well exposed in the river and in order to gain even a moderately complete idea of the formation it is necessary to include outcrops on Quebrada Merecure and Quebrada Carapita in the type section, as shown on the map (Pl. 1). The whole course of Quebrada Merecure lies within the outcrop area of the formation.

LITHOLOGY: The formation is characterized lithologically by hard whitish-gray and pinkish-gray, quartzitic sandstones (Pl. 7, figs. 3 and 4). Although these probably make up less than half the total thickness of the formation they constitute almost the only well-known outcrop in the type locality. Because of their resistance to erosion they form prominent ridges; the less-resistant strata between them are largely concealed by boulders and alluvial debris.

The sandstone at the base of the formation is particularly prominent and is well exposed on the Rio Querecual where a rock gorge with waterfalls marks its outcrop. This sandstone is more than 600 feet thick, medium- to thick-bedded, whitish gray to pinkish gray, very hard, aphanitic in appearance, and quartzitic in part. Locally it is laminated but shows no tendency to break along laminations. There is a foot or two of finely conglomeratic sandstone at the base but in general the sandstone is of medium to fine grain. The clean, purely quartzose character of this sandstone and the lack of calcareous cement or glauconite distinguish it from sandstones in the underlying Santa Anita formation. To the east of the river it forms the prominent rock cliffs of Cerro de los Jabillos.

Exposures of the middle portion of the Merecure formation are poor. The section apparently includes a number of sandstones similar to those at the base of the formation but of lesser thickness and alternating with intervals of shale. The shales form valleys largely covered with alluvial debris. The sandstones form ridges but the rock is broken by jointing and is rarely in place due to slump of the joint blocks down the hill sides. The best outcrops of this part of the formation, seen on Quebrada Merecure, include hard, whitish to pinkish-gray, quartzitic sandstone, brownish-gray, soft to medium hard, sugary sandstone, brownish-gray siltstones, and brown and brownish-gray silty shale. Some of the siltstones and fine sandstones show carbonaceous laminae.

In the upper part of the formation resistant sandstones form the prominent ridge to which belong Cerro Cambural, Cerro de los Lallosos, Cerro La Cruz, and Cerro Acosteño. Outcrops consist principally of massive, hard, whitish, pinkish, and buff quartzitic sandstone and quartz-granule conglomerate, thin- to medium-bedded,

FIGURE 1. SANDSTONE DIKES CUTTING THROUGH SHALE
In San Antonio formation on Cerro San Antonio just north of Bergantin. Shale strikes N 85° E and dips 20° N; sandstone dike strikes N and dips 70° W.

FIGURE 2. TYPICAL GRIT AND CONGLOMERATE
Of basal part of Santa Ines formation on Quebrada Carapita.

FIGURE 3. HARD GRAY SANDSTONE WITH THIN SEAMS OF BLACK CHERT CONGLOMERATE
In Santa Ines formation on Rio Querecual south of Capaya.

FIGURE 1. VERY HARD BLUISH-GRAY DOLOMITIC SILTSTONE
Caratas member of Santa Anita formation; weathers to characteristically rounded forms.

FIGURE 2. CONTACT BETWEEN SANTA ANITA FORMATION (RIGHT) AND MERECURE FORMATION (LEFT)
Hammer point is at contact. Note tube-fillings of pebbly Merecure sandstone extending down into soft melanterite-covered sandstone bed at top of Santa Anita formation.

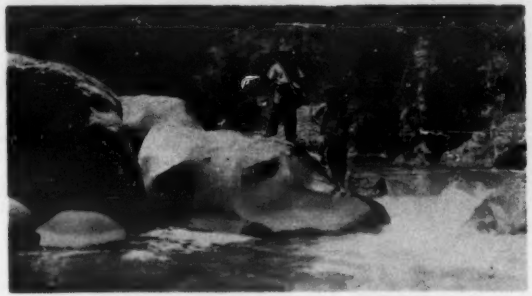

FIGURE 3. QUARTZITIC SANDSTONE
Near base of Merecure formation on Rio Querecual.

FIGURE 4. CHARACTERISTIC BLOCKY JOINTING
Quartzitic sandstone in Merecure formation.

SANTA ANITA AND MERECURE FORMATIONS

ripple-marked and cross-bedded, fine-grained sandstone, and medium hard pink, buff, and brown sugary sandstones. There are also hard brownish siltstones, brown silty shales, and light-gray shales which weather red-mottled. This part of the formation is best exposed on Quebrada Carapita, and the uppermost portion of the columnar section (Pl. 9B) is taken from this quebrada.

FORMATION BOUNDARIES: The contact between the Santa Anita and Merecure formations is placed above the gray, glauconitic, calcareous shales, blue-gray calcareous siltstones, and dirty-gray glauconitic sandstones typical of the Caratas member of the Santa Anita formation and just at the base of the characteristic hard, quartzitic, whitish-gray to pinkish quartzose sandstones of the Merecure formation. The section at the contact on the Rio Querecual is perfectly exposed and from top to bottom is as follows (Pl. 7, fig. 2):

600 feet .....Largely very hard whitish to pinkish-gray quartzitic sandstone.
1-2 feet .....Hard, gray, gritty, micaceous, quartzitic sandstone and quartz-granule conglomerate with carbonaceous inclusions. Tubes and fingers of the sandstone and granule conglomerate extend downward for several inches into the underlying rock.

Contact

1-2 feet .....Yellowish argillaceous sandstone impregnated near the surface with melanterite.
20 feet .....Light-gray calcareous shale with numerous thin seams of small discoidal or nodular calcareous and ferruginous concretions (2-3 inches in diameter).
20 feet .....Brownish-gray calcareous shale with siltstone.
10 feet .....Hard gray glauconitic and limonitic grit and granule conglomerate.

The contact between the Merecure formation and the overlying Carapita formation is placed above the highest of the typical light-colored, quartzose, sugary sandstone and quartzites of the Merecure formation and below the lowest of the distinctive brownish-greenish gray or "pepper and salt" sandstones of the Carapita formation. The contact is well exposed on Quebrada Carapita where the two types of sandstone are in juxtaposition. Where there is a shaly interval between the sandstone outcrops, as on Cerro de los Lallosos or on the Rio Querecual, it is more difficult to establish the contact accurately. Red and gray mottled shales are usually to be assigned to the Merecure formation. Also, it is sometimes possible to find Foraminifera in the lowermost Carapita formation shales, while the Merecure shales are barren.

THICKNESS: Estimates of the thickness of the Merecure formation in the type locality are probably not very accurate owing to the scarcity of good dips and strikes in the middle portion of the formation and the difficulty of evaluating the extent of overturning and possible faulting. The writer has estimated a thickness of 5725 feet for the type locality, but at best this is only a rough approximation.

MINERALOGY: Heavy mineral analyses show considerable variation, especially in the upper part of the formation. The following average figures may be given for the less variable minerals: ilmenite—2, leucoxene—4, zircon—4, rutile—2. Garnet and chloritoid are absent or very rare in all the typical sandstones and quartzites of the formation, but appear in abundance in a few fine-grained sandstones in the upper part of the formation. Staurolite is usually absent but a few grains have been found in some samples. Brookite is variable. Secondary mineral matter other than silica is rare.

PALEONTOLOGY: No fossils have been found in the Merecure formation of the type locality. The hard sandstones give little promise of carrying fossil remains but it is

probable that further investigation of the shaly intervals through pits or borings will yield fossils of some sort. In the Naricual area to the west excellent plant fossils have been obtained from what is probably the same formation, and sediments both to the east and west which are believed to be the time equivalents of the Merecure formation carry orbitoid Foraminifera.

AGE AND CORRELATION: Because of the lack of fossils in the type locality, conclusions on the age of the Merecure formation must be based largely on its stratigraphic position in the Rio Querecual section between Paleocene and Oligocene sediments and on correlation with other areas. The formation may be traced with considerable assurance westward from the Bergantin-Santa Ines area into the prominent ridge (Cerro Grande) separating the Naricual and Capiricual valleys southeast of Barcelona. Here it appears to include not only quartzitic sandstones but in its upper part coarse pebble conglomerates and in its lower part the famous Naricual coal measures.

The formation is not known west of the Barcelona-San Mateo road but, about 50 kilometers west of Barcelona, between Piritu and the Rio Unare, sediments believed to be the time equivalents of the Merecure formation are exposed. They include conglomerates and coals similar to those of Naricual but also in part consist of massive orbitoidal reef limestones, which are particularly well exposed on Cerro Peñas Blancas and El Picacho a few kilometers east of the river. The Peñas Blancas limestone contains *Lepidocyclina trinitatis* H. Douvillé, *Lepidocyclina (Pliolepidina) tobleri* H. Douvillé, *Lepidocyclina* sp. (microspheric form of *L. tobleri* ?), *Echinolampus ovumserpentis* Guppy, *Rotularia* sp., and an abundance of *Lithothamnium* sp. It may be rather definitely correlated with the Upper Eocene limestone of Vista Bella quarry in Trinidad (Mount Moriah formation) and with Bed No. 6 of Soldado Rock,[80] and it is probably equivalent to the Upper Eocene orbitoidal limestone of Woodring[81] from the State of Zamora, Venezuela. Woodring notes the presence of a megalospheric and microspheric couple in this limestone and identifies the megalospheric form with *Lepidocyclina panamensis* Cushman (=*L. tobleri* Douvillé ?). A similar couple is present in the Peñas Blancas limestone. Dietrich[82] and Liddle[83] have considered the Peñas Blancas limestone Oligocene but paleontologic data definitely favor an Upper Eocene age. Dietrich identified *L. panamensis* but considered it as evidence of Oligocene age, probably because this species was first described from beds in Panama which were at that time believed to be of Oligocene age. Bed No. 6 on Soldado Rock is considered to be of Bartonian or early Upper Eocene age while the slightly higher horizon of Bed No. 8 on Soldado Rock constitutes Maury's Boca de Serpiente formation which is referred to the Ludian or uppermost Eocene.[84] The Peñas Blancas limestone seems to correlate with Bed No. 6 rather than Bed No. 8 and therefore this limestone and its equivalent horizon in the Merecure formation are probably of Bartonian rather than Ludian age.

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[80] C. J. Maury: *Venezuelan stratigraphy*, Am. Jour. Sci., 5th ser., vol. 9, no. 53 (1925) p. 411-414; *The Soldado rock type section of Eocene*, Jour. Geol., vol. 37, no. 2 (1929) p. 177-181; *Bartonian and Ludian upper Eocene in the western hemisphere*, Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 375-376.

H. G. Kugler: *op. cit.*

H. Douvillé: *Les Orbitoides de l'Ile de la Trinité*, Acad. Sci. Paris, C. R., vol. 161 (1915) p. 87-93; vol. 164 (1917) p. 841-847.

[81] W. P. Woodring: *Marine Eocene deposits on the east slope of the Venezuelan Andes*, Am. Assoc. Petrol. Geol., Bull., vol. 11, no. 9 (1927) p. 992-996.

[82] W. O. Dietrich: *Zur Palaontologie und Stratigraphie der Kreide und des Tertiars in der ostkaribischen Kordillere Venezuelas*, Zentralbl. Mineral., Geol., Paläont., no. 6 (March 15, 1924) p. 188.

[83] R. A. Liddle: *Outlines of Venezuelan stratigraphy*, Pan-Am. Geol., vol. 57 (1932) p. 175.

[84] C. J. Maury: *Bartonian and Ludian upper Eocene in the western hemisphere*, Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 375-376.

Eastward from the Bergantin-Santa Ines area the prominent basal sandstone of the Merecure formation may be traced for many kilometers. On Rio Areo 50 kilometers east of Santa Ines, orbitoidal limestones associated with dark shales and quartzitic sandstones are probably time equivalents of the Merecure formation. Like those of Peñas Blancas the Rio Areo limestones are definitely of Upper Eocene age.

STRATIGRAPHIC RELATIONS: There is little direct evidence of unconformity between the Merecure formation and the underlying Santa Anita formation in the Rio Querecual section. Tubes of Merecure sandstone extend downward a few inches into the top of the Santa Anita formation, suggesting the work of boring animals, and there is a thin, poorly defined basal conglomerate just above the contact. Both these features suggest at least shallow-water conditions, but neither requires actual emergence. There is no direct evidence of angular relation nor of erosional unconformity. At the same time the marked change in lithology and the fact that the Santa Anita formation is of Upper Cretaceous-Paleocene age while the Merecure formation is at least in part of Upper Eocene age suggest the strong possibility of a break between these two formations. Sufficient information is not yet available to show whether the Merecure formation rests on different horizons in the Santa Anita formation from place to place, but the writer is inclined to believe that such a condition will be found.

Throughout much of northern South America and the Caribbean region, the Upper Eocene was marked by a great transgression and deposits of this age rest unconformably on various older rocks. Olsson [95] considers the unconformity at the base of the Upper Eocene in Peru as the most important stratigraphic break in the whole Tertiary of that region. In Trinidad the Mount Moriah formation of Upper Eocene age rests unconformably on Paleocene and Cretaceous rocks.[96] On Soldado Rock an unconformity seems to intervene between Maury's Soldado formation (Paleocene) and the Bartonian Upper Eocene sediments to which her Bed No. 6 belongs.[97] In Curacao and Bonaire, Upper Eocene limestones rest unconformably on rocks of Paleocene, Cretaceous, or greater age and a similar condition prevails in many other West Indian islands.[98] It seems probable that further work will definitely prove this same relation between the Merecure formation and older sediments in northeastern Venezuela.

Direct evidence of unconformity between the Merecure formation and the overlying Oligocene Carapita formation is also lacking in the Santa Ines area. However, the general lithologic, mineralogic, and paleontologic differences between the two formations suggest that they are separated by at least a hiatus in deposition, and it seems probable that further work will prove a regional unconformity. In Peru, Olsson [99] finds an unconformity separating the Bartonian Talara formation from the Ludian Saman formation and, in western Venezuela, Senn [100] reports an angular unconformity within the Upper Eocene and an unconformity separating Lower Oligocene from Middle Oligocene sediments. Since the bulk of the Carapita formation is of Upper Oligocene age, an unconformity between the Merecure and Carapita formations might be expected on the basis of regional stratigraphy.

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[95] A. A. Olsson: *Contributions to the Tertiary paleontology of northern Peru, Part III, Eocene Mollusca*, Bull. Am. Paleont., vol. 17, no. 62 (1930) p. 11.

[96] H. G. Kugler: *Summary digest of geology of Trinidad*, Am. Assoc. Petrol. Geog., Bull., vol. 20 (1936) p. 1443.

[97] H. G. Kugler: *Das Eozänprofil von Soldado Rock bei Trinidad*, Eclogae geol. Helv., vol. 18, no. 2 (1923) p. 256-257.

[98] L. Rutten: *Alte Land- und Meeresverbindungen in West-Indien und Zentralamerika*, Geol. Rundschau, Bd. 26 (1935) p. 84.

[99] A. A. Olsson: *op. cit.*, p. 8.

[100] Alfred Senn: *op. cit.*, p. 59-60.

DISTINCTIVE FEATURES: The Merecure formation of the type locality is distinguished principally by its pure, quartzose, light-colored, quartzitic sandstones and quartzites. These differ from hard sandstones in the Santa Anita formation by their pureness, their lighter color, and the lack of carbonate cement and glauconite. In general they are also less impure, harder, and of different heavy mineral content than the sandstones of younger formations. The shales are as yet poorly known but apparently lack the characteristic Foraminifera of the overlying and underlying formations.

CARAPITA FORMATION

(Plate 9, section C)

NAME AND TYPE LOCALITY: The formation is named from Quebrada Carapita, a tributary of the Rio Querecual which rises in the foothills north of Santa Ines. The type section of the formation is on this quebrada from a point about 5 kilometers north of Santa Ines to a point about 2 kilometers north of Santa Ines where the quebrada swings sharply westward at the north edge of prominent sandstone and conglomerate ridges of the overlying Santa Ines formation (Pl. 1).

The formation is also exposed on the Rio Querecual itself in the vicinity of Capaya between the top of the Merecure formation and the big bend in the river north of Cerro Potrerito. However, the section here is poor, structurally disturbed, and abnormally thin so it has seemed desirable to designate as type the Quebrada Carapita section which is undoubtedly the best outcrop section of this formation.

LITHOLOGY: The Carapita formation as a whole consists dominantly of shale but may be divided into two members because of the presence of sandstones and sandy shales in the lower part.

The lower member of the Carapita formation consists of about 2000 feet of sandstones and sandy and silty shales. It occupies the interval from Sample E-3099 to E-4019 (Pl. 1). The sandstones are of a very distinctive appearance and readily differentiated from those lower in the section (Plate 5, fig. 2). They are typically of fine even texture and are gray, greenish gray, brownish-greenish gray, buff brown and "pepper and salt" color. They are usually thick-bedded but at the same time characteristically show fine lamination and cross lamination. The laminae are frequently very micaceous and carbonaceous. Individual sandstones attain thicknesses of as much as 40 feet.

The shales of this member are gray or brownish gray. They are almost invariably sandy or silty and frequently contain sand laminae or thin beds of sandstone. Thin seams of discoidal clay-ironstone concretions are characteristic. A bed of coal a foot thick was noted near the base of the section both on Quebrada Carapita and on Quebrada Capaya.

The upper or main member of the Carapita formation on Quebrada Carapita is about 7000 feet thick. Outcrops consist almost entirely of dark-gray or brownish-gray, fissile, more or less foraminiferal shales forming characteristically steep-walled faces along the quebrada course (Plate 5, fig. 3). Thin seams of clay-ironstone or of discoidal clay-ironstone concretions are common. There are a few thin beds of fine-grained sandstone of the type common in the lower member. At the locality of Sample E-4031 there is an anomalous 2-foot bed of coarse conglomerate with pebbles of chert, sandstone, and quartz which appears suddenly in the midst of shales and sandy shales.

FORMATION BOUNDARIES: The contact of the Carapita formation with the underlying Merecure formation is placed where the light-colored, massive, medium- to coarse-grained, sugary or quartzitic sandstones of the Merecure formation give way to the characteristic, fine-grained, somber-hued, laminated sandstones of the Carapita

formation. The two types of sandstone form boulders of distinctive character: those of the Merecure formation tend to be rounded and show subconchoidal fracture surfaces; and those of the Carapita formation are more blocky or slabby. The contact is well exposed on Quebrada Carapita where 20 feet of massive, whitish-buff, medium- to coarse-grained, quartzitic sandstone at the locality of Sample E-3099 is overlain by 30 feet of thin-bedded, gray to buff, fine-grained sandstone with carbonaceous laminae.

The top of the Carapita formation in the type section is very definitely determined by the abrupt appearance of coarse brown sandstones and pebble and cobble conglomerates of the Santa Ines formation, forming prominent strike ridges at the south border of the Carapita shale outcrop. A sharp change in dip coincides with the lithologic change. Throughout the area in general the top of the Carapita formation may be placed at the base of the more or less continuous sandstone and conglomerate series overlying the typical development of Carapita shale, although, as will be pointed out, this contact does not coincide exactly with a time horizon, for individual sandstone beds near the contact appear to grade eastward into shales. Thus the top of the Carapita formation on the Rio Querecual is at a slightly older time-stratigraphic horizon than the top on Quebrada Carapita, and the conglomerate marking the base of the Santa Ines formation on Quebrada Carapita lies considerably above the base of that formation on the Rio Querecual. The relations are brought out on the map (Pl. 1) by the trace of individual sandstone beds between Santa Ines and Capaya.

THICKNESS: The total measured thickness of the Carapita formation in the type section is about 9000 feet, of which 2000 feet belong to the lower sandy member and 7000 feet to the upper shale member. Dips and strikes are fairly regular but in the upper part of the formation they are rather far apart and there are long covered intervals for which the attitude of the strata can only be assumed. The whole section is apparently dipping northward, but observation of the cross lamination and scour-and-fill structure in the sandstones shows definitely that the top of the beds is to the south and that they have been overturned.

The formation thins rapidly westward from the type section as a result both of lateral variation and structural disturbance. On the Rio Querecual the total thickness is probably no more than 4000 feet. The incompetent shales of the formation appear to have been squeezed and distorted between the Eocene and Miocene sandstones during the formation of the Capaya Z-flexure (Pl. 1).

MINERALOGY: Sandstones of the type section of the Carapita formation are characterized by the persistent presence of garnet and chloritoid among the heavy detrital minerals. The garnet is of the etched type so common in some Eocene sandstones of western Venezuela.[101] There are rare occurrences of staurolite, and glaucophane was noted in one sample from the type section. The average detrital heavy mineral distribution for the type section is as follows: ilmenite—3, leucoxene—3, zircon—3, garnet—2, staurolite—0-1, rutile—2, anatase—1, brookite—0-1, chloritoid—1-2.

Siderite is common in concretions in the shales and some of the sandstones are slightly calcareous. No glauconite has been noticed. Pebbles of dark chert occur in the conglomerate of Sample E-4031 on Quebrada Carapita and the "pepper and salt" sandstones of the lower member owe their appearance to grains of black chert and white, partially decomposed feldspar.

PALEONTOLOGY: No large fossils have been found in the type section of the Carapita formation but almost all of the "Carapita shales" carry at least a few foraminifera

[101] H. D. Hedberg: *Some aspects of sedimentary petrography in relation to stratigraphy in the Bolivar Coast Fields of the Maracaibo Basin, Venezuela*, Jour. Paleont., vol. 2, no. 1 (1928) p. 41.
M. N. Bramlette: *Notes and news: Natural etching of detrital garnet*, Am. Mineral., vol. 14, no. 9 (1929) p. 336.

and those of the middle part of the formation are highly foraminiferal. On the basis of the microfauna, the type section has been divided into three zones (see columnar section, Plate 9, C). The lower zone carries a rather scanty assemblage of arenaceous forms, the middle zone contains a varied microfauna of both calcareous and arenaceous Foraminifera, and the upper zone contains a scanty fauna which is largely arenaceous but carries some calcareous forms. The following species are known from the type section:[102]

Ammobaculites sp.
Ammodiscus incertus (d'Orbigny)
Ammodiscus parianus Hedberg
Anomalina mecatepecensis Nuttall
Anomalina nolani Hedberg
Anomalina pariana Hedberg
Bathysiphon carapitanus Hedberg
Bolivina aenariensis (Costa) var. *carapitana* Hedberg
Bolivina alazanensis Cushman var. *venezuelana* Hedberg
Bulimina bleeckeri Hedberg
Bulimina cf. *inflata* Seguenza
Bulimina pupoides (?) d'Orbigny
Cassidulina carapitana Hedberg
Cassidulina subglobosa Brady
Chilostomella oolina Schwager
Clavulina curta Galloway and Morrey
Cibicides americanus (Cushman)
Cibicides floridanus (Cushman)
Cibicides mantaensis (Galloway and Morrey)
Cyclammina cancellata Brady
Dentalina adolphina d'Orbigny
Dorothia asiphonia (Andreae)
Dorothia nuttalli Cushman
Ellipsonodosaria verneuili (d'Orbigny)
Eponides byramensis Cushman
Eponides crebbsi Hedberg
Eponides umbonatus (Reuss) var. *ecuadorensis* Galloway and Morrey
Gaudryina jacksonensis Cushman
Globigerina sp.
Globigerina venezuelana Hedberg
Globigerinella sp.
Globobulimina cf. *pacifica* Cushman
Gyroidina soldanii d'Orbigny
Haplophragmoides sp.
Heterostomella halconi Hedberg
Hormosina ovaliformis Cushman
Lagena sp.
Lenticulina sp.
Marginulina glabra d'Orbigny
Marginulina sublituus (Nuttall)
Marginulina wallacei Hedberg
Miliolidae undif.
Miogypsina sp.
Nodosaria longiscata d'Orbigny
Nodosaria nuttalli Hedberg
Nodosaria pariana Hedberg
Nodosaria raphanistrum (Linné) var. *caribbeana* Hedberg
Nodosaria vertebralis (Batsch)
Nonion belridgensis Barbat and Johnson
Planularia venezuelana Hedberg
Plectofrondicularia californica Cushman and Stewart
Plectofrondicularia vaughani Cushman
Pseudoglandulina comatula (Cushman)
Robulus calcar (Linné)
Robulus clericii (Fornasini)
Robulus sp.
Rzehakina venezuelana Hedberg
Saccammina sp.
Saracenaria senni Hedberg
Sigmoilina orinocoensis Hedberg
Sigmoilina tenuis (Czjzek)
Siphogenerina transversa Cushman
Siphonina tenuicarinata Cushman
Sphaeroidina variabilis Reuss
Textularia grenadana Hedberg
Textularia mexicana Cushman
Textularia sp.
Textulariella barrettii (Jones and Parker)
Trochammina cf. *conglobata* Brady
Uvigerina carapitana Hedberg
Uvigerina pygmaea d'Orbigny var. *capayana* Hedberg
Valvulineria venezuelana Hedberg
Verneuilina sp.

[102] The composition of the foraminiferal fauna of the Carapita formation, description and distribution of individual species, probable ecologic environment, and relation to other Tertiary foraminiferal faunas of tropical America are discussed in a paper awaiting publication in the Journal of Paleontology.

Comparison of the Carapita fauna with the foraminiferal assemblages living today in marine waters of tropical America indicates that the formation originated in moderately deep water. Those species still living are largely confined to depths of more than 100 fathoms and the general composition of the Carapita fauna is distinctly different from that of the typical shallow water Middle Tertiary assemblages of this region. At the same time, the rapid gradation of the Carapita shales westward into coarsely clastic deposits indicates that the formation must have been deposited relatively near shore.

AGE AND CORRELATION: Study of the foraminiferal fauna of the Carapita formation and comparison with other faunas of tropical America have led to the conclusion that the middle zone of the Carapita formation is the time equivalent of the El Mene de Acosta beds (Agua Clara stage) of the State of Falcon in western Venezuela[103] and of the shales underlying the Guaracara-Tamana limestone horizon of Trinidad (Alley Creek formation of Kugler).[104] All of these seem to be of approximate Upper Oligocene (Aquitanian or Chattian) age and are probably equivalent, at least in part, to the Culebra stage of Panama-Costa Rica, the Anguilla stage of the West Indies, the Heath stage of Peru, the Zemorrian stage of California, and the Vicksburg stage of the Gulf Coast of the United States.

While the middle zone of the Carapita formation may be considered approximately Upper Oligocene, the formation is very thick and it is entirely possible that the basal part may be of Middle Oligocene age whereas the upper part of the type section may extend into the lowermost Miocene. Such a time range for the formation as a whole would correspond to those of the analogous Middle Oligocene to lowermost Miocene depositional cycles represented by the Mancora, Heath, and lower Zorritos formations of Peru and the Bohio, Culebra, Emperador, and Caimito formations of Panama.[105]

The Carapita formation is probably equivalent to some part of the "Lower Miocene-Oligocene black shales" of the State of Monagas, mentioned by Manger.[106] Kugler[107] has correlated the Alley Creek formation of Trinidad with the Bissex Hill marl of Barbados which on this basis is, therefore, also approximately equivalent to the Carapita formation.

STRATIGRAPHIC RELATIONS: There is no direct evidence of unconformity between the Carapita formation and the underlying Merecure formation. On the other hand, there are broad differences between the two formations which indicate that they were formed under quite different paleogeographic surroundings and suggest that they may be separated by a considerable time interval. The sandstones of the two formations are lithologically distinct and the differences in their detrital mineral content indicate different sources. Shales of the Carapita formation commonly carry marine Foraminifera while those of the Merecure formation are barren. In this region there is in general a rather marked decrease in the degree of induration of the sediments above the top of the Merecure formation. Finally, the Merecure formation is probably of Upper Eocene age while the Carapita formation in its middle part is of Upper

[103] Alfred Senn: *Die stratigraphische Verbreitung der Tertiaren Orbitoiden mit spezieller Berucksichtigung ihres Vorkommens in Nord-Venezuela und Nord-Marokko*, Eclogae geol. Helv., vol. 28, no. 1 (1935) p. 74-78.

[104] H. G. Kugler: *Summary digest of geology of Trinidad*, Am. Assoc. Petrol. Geol., Bull., vol. 20 (1936) p. 1445.

[105] A. A. Olsson: *Contributions to the Tertiary Paleontology of northern Peru, Part IV, The Peruvian Oligocene*, Bull. Am. Paleont., vol. 17, no. 63 (1931) p. 30.

[106] G. E. Manger: *A late Pliocene or post-Pliocene major uplift of the Coast Range of the Venezuelan Andes*, Am. Jour. Sci., 5th ser., vol. 24 (July 1932) p. 33.

[107] H. G. Kugler: *op. cit.*, p. 1445.

Oligocene age. The age of the lower part of the Carapita formation is not known but it seems improbable that it represents both Middle and Lower Oligocene. Definite proof of unconformity must await studies of the contact over broader areas. The uppermost Eocene-Lower Oligocene Agua Negra formation of Senn[108] in western Venezuela seems to have no equivalent in eastern Venezuela and probably represents the interval between Merecure and Carapita time. It is separated from the Middle Oligocene San Luis formation by an unconformity.

Relations between the Carapita formation and the overlying Santa Ines formation are not uniform throughout this general area. In the type section on Quebrada Carapita, there is an abrupt change in lithology at the contact and also a change in dip from 70° N in the upper part of the Carapita formation to 75° S in the basal beds of the Santa Ines formation. Both erosional unconformity and angular discordance are suggested and on Rio Oregano, 15 kilometers east of the type section, there is apparently a definite angular unconformity with gently dipping Santa Ines beds resting on vertical Carapita shale. Westward from Quebrada Carapita, however, not only does evidence of angular relation between the two formations disappear suddenly but there is definite lateral gradation of shales in the upper part of the Carapita formation into sandstones of the lower Santa Ines. The boundary line between formations cuts sharply across time-stratigraphic horizons as successively lower sandstones appear below the horizon of the contact on Quebrada Carapita. Thus south of Capaya the horizon which marked the contact on Quebrada Carapita lies nearly 1000 feet above the base of the Santa Ines formation and only a few kilometers west of Capaya the rapidly narrowing outcrop belt of the upper member of the Carapita formation seems to grade out completely into the Santa Ines formation. The anomalous condition is thus presented of an angular unconformity, between marine shales below and coarse sandstones and conglomerates above, grading out in the direction in which the coarseness of sediments in both formations is increasing.

Distinctive Features: The Carapita formation is distinguished from all older formations by the characteristic color and texture of its sandstones, by the garnet-chloritoid mineral suite which is unknown in formations older than the Merecure and is rare in that formation, by the bulk of shale which it contains, and by its characteristic Foraminifera. It is distinguished from younger formations by its characteristic foraminiferal fauna, by its great thickness of dark shales, and by the rarity of staurolite in heavy mineral separates.

SANTA INES FORMATION

(Plate 9, section D)

Name and Type Locality: The formation is named from the town of Santa Ines, District of Libertad, State of Anzoategui. It is not possible to designate any one river or quebrada section as type because of the great width of the formation outcrop belt. The type locality is from the vicinity of the town of Santa Ines southward some 20 kilometers to and including the Dividive ridges east of the town of San Mateo. The base of the formation in the type locality coincides with the north edge of the sandstone and conglomerate ridges overlying the Carapita shale in Quebrada Carapita, and this contact extends westward around the Capaya Z-flexure and along the base of Cerro Potrerito just south of Capaya (Pl. 1). The top of the formation of the type locality approximately coincides with the south edge of the prominent Dividive ridge which extends eastward from San Mateo. The name was first pub-

[108] Alfred Senn: *op. cit.*, p. 59.

lished by Garner[109] in 1926. His type locality is designated as "small hills north of Santa Ines".

LITHOLOGY: The great thickness of the sediments included here in the Santa Ines formation (10,000 to 20,000 feet) will probably eventually be divided into several members or perhaps formations. In a general way, however, all these sediments are unified by the presence of calcareous grits, sandstones, sandy limestones, and conglomerates; brackish and shallow-water marine mollusks; and evidence of rapid deposition near source. Until known in greater detail, they must be left in a single formation.

Only the lower portion of the formation is known on Rio Querecual and its tributaries. On Quebrada Carapita about 6000 feet of the lower part of the Santa Ines formation is exposed above the Carapita shales. In this section only the resistant ridge-forming beds appear at the surface, and the intervening strata (probably shales and claystones) are entirely concealed by surface alluvium. The exposed sediments consist almost entirely of weathered buff, yellow and brown, or brown and gray mottled gritty sandstones and conglomerates which are generally calcareously cemented (Pl. 6, fig. 2). Pebbles are largely of black chert, gray quartzitic sandstone, and light-gray chert; and reach a maximum diameter of 2 to 3 inches.

Because of lateral variation in lithology, the base of the Santa Ines formation is stratigraphically lower on Rio Querecual than on Quebrada Carapita and includes more than 1000 feet of section equivalent to the upper part of the Carapita formation on Quebrada Carapita. This basal part of the Santa Ines formation on Rio Querecual consists of hard gray, thick-bedded but laminated, fine-grained sandstones and gray fissile shales with seams of clay-ironstone concretions. The interval is assigned to the Santa Ines formation largely because sandstones are more prominent than in the upper part of the type Carapita formation. Also, Foraminifera indicate that the shales were deposited in shallower water than those of the typical Carapita formation.

About 1000 feet above the base of the formation on Rio Querecual is an exposure of more than 100 feet of bluish and greenish-gray foraminiferal shale and 300 feet above the top of this shale is a fine-grained sandstone similar to those of the Carapita formation but with thin, sharply defined seams of black chert conglomerate containing pebbles as much as an inch in diameter though usually much smaller. About 1700 feet above the base of the formation is another sandstone with seams of conglomerate (Sample S-2582) which probably is the same bed as that which marks the base of the formation on the Quebrada Carapita. Little of this conglomerate outcrops on the river but the same bed forms the crest of the high ridge known as Cerro Potrerito and here the conglomeratic character is well developed. The remaining 3000 feet of section exposed above this point in the Rio Querecual consist largely of gray, greenish-gray, brownish, brownish-green, and "pepper and salt" sandstones and gritty sandstones with streaks of black chert conglomerate (Pl. 6, fig. 3). Many of these beds, where not conglomeratic, are identical in character with the sandstones in the lower member of the Carapita formation. There are a few exposures of gray and greenish-gray silty shale with poorly preserved fossils.

Red and gray mottled claystones are exposed on the river a few hundred meters below the mouth of Quebrada Macal and mottled claystones also occur in the hills near Santa Ines.

The middle portion of the Santa Ines formation is exposed in the hills south of the Santa Ines-Barcelona road. This section has not been accurately measured nor

[109] A. H. Garner: *Suggested nomenclature and correlation of the geological formations in Venezuela*, Am. Inst. Min. Metall. Eng., Tr. (April 1926) p. 181.

studied in detail. Outcrops consist largely of yellowish- and brownish-weathering sandstones, grits, and conglomerates, and thin, sandy, fossiliferous limestones. Near the axis of the Caratas syncline are some whitish to reddish, hard, quartzitic sandstones. Many of the sandstones and conglomerates are calcareous. There are some lignites and carbonaceous and lignitic shales. Weathered surfaces of the carbonaceous shales are frequently coated with jarosite. Small nodules of white alunite are also commonly associated with these shales, and this mineral occurs locally in thin seams.

The upper part of the formation is exposed between the course of Rio Aragua and the road from San Mateo to Orijuan and forms the southern flank of the broad gentle anticline to the south of the Bergantin structure. This part of the formation is more shaly than that below and is rather poorly exposed. Outcrops consist of gray, fissile, fossiliferous shale with clay-ironstone concretions, light-gray gypsiferous shale, mottled claystones, brownish sandstones, and sandy limestones. The uppermost part of the formation, a series of thin, hard, sandy and conglomeratic limestones and calcareous sandstones, forms Dividive ridge extending eastward from San Mateo. This has sometimes been referred to as the San Mateo member.

Formation Boundaries: The contact between the Santa Ines formation and the Carapita formation is placed at the base of the first prominent sandstone or conglomerate of the more or less continuous series of these beds overlying the typical shales of the Carapita formation. In the Quebrada Carapita section, this contact is definite and there is even evidence of an angular unconformity. Westward from this section, however, there is no indication of unconformity, and the shales of the Carapita formation grade laterally into sandstones in this direction. Ridge after ridge of sandstone appears below the contact horizon on Quebrada Carapita as this horizon is traced westward. Since these sandstones are identical to some of the sandstones above the contact horizon in Quebrada Carapita and since there is no longer any indication of unconformity, the boundary line between the two formations (Pl. 1) must be drawn arbitrarily across the east ends and north sides of these ridges although this makes the formation contact cut across time lines and makes the upper part of the Carapita formation on Quebrada Carapita the time equivalent of the basal Santa Ines formation on Rio Querecual.

The top of the Santa Ines formation has been placed arbitrarily at the top of the topographically prominent limestones and sandstones of the Dividive ridge and separates this formation from the less consolidated claystones, shales, and sandstones of younger age which lie between this ridge and the mesa front.

Thickness: No accurate measurements of the thickness of the formation have been made by the writer. The lower part of the formation exposed on Quebrada Carapita is about 6000 feet thick and the total thickness in the type locality must be well over 10,000 feet. A thickness of 19,000 feet was calculated by Clemente de Juana, who measured this section for another company. Much of the apparent thickness may be due to depositional dip and the overlapping of inclined lenses formed during the rapid deposition of the coarse clastics in the lower part of the formation.

Mineralogy: The mineralogy of heavy detritals in the Santa Ines formation is very similar to that of the underlying Carapita formation. Both are characterized by the persistent presence of garnet and chloritoid and in both the garnet is usually of the etched type. However, while staurolite is very rare in the Carapita formation it is almost always present in samples from the Santa Ines formation. The average mineral distribution in samples from the lower part of the formation (Santa Ines area) is as follows: ilmenite—3-4, leucoxene—3-4, zircon—3-4, tourmaline—1, garnet—2, staurolite—1, glaucophane—0-1, rutile—1-2, anatase—0-1, brookite—0-1, chloritoid—1.

The principal secondary mineral is calcite, which is commonly present as cement. Some of the shales carry siderite. No glauconite has been noticed.

A yellowish mineral, commonly forming powdery efflorescences on the surfaces of dark carbonaceous shales in the Santa Ines formation, is believed to be jarosite, $K_2Fe_6(OH)_{12}(SO_4)_4$. It also occurs as yellowish nodules on weathered shale slopes. An analysis of some of this material by James D. Hedberg shows a sulphate content of about 29 per cent. This is low for jarosite, probably owing to a mixture of clayey matter with the mineral. This mineral is a common weathering product on the surfaces of carbonaceous and pyritic shales throughout the whole of Venezuela. It is the "sulphur salt" to which Liddle[110] makes frequent reference.

At Paso Arecife, on the trail east of Santa Ines along the Rio Oregano, the writer found several thin seams of a pure white, brittle, clay-like material in a loose, gray, coarse-grained sandstone associated with lignitic shales. The seams are only 2 to 3 inches thick and are laterally discontinuous. With an oil immersion lens under the petrographic microscope the material was resolved into minute, colorless, tabular crystals with a refractive index of about 1.57. Through courtesy of C. S. Corbett some of the mineral was sent to A. N. Winchell at the University of Wisconsin where an X-ray analysis showed that it was alunite. This determination was confirmed by a chemical analysis by James D. Hedberg, which gave the following composition:

	Per cent
H_2O at 110° C.	0.36
H_2O (loss on ignition)	7.80
SiO_2	3.20
Al_2O_3	37.36
Fe_2O_3	2.12
TiO_2	trace
CaO	0.58
MgO	0.00
Na_2O and/or K_2O	12.58
SO_3	34.60

In addition to the occurrence at Paso Arecife, alunite is widespread throughout the middle part of the Santa Ines formation, appearing usually as nodules on weathered shale slopes and more rarely as thin seams in bedded strata. There is no reason to believe that it is in any way associated with hydrothermal alteration and the occurrence is therefore of particular interest.

Paleontology and Age: Molluscan fossils are fairly common in both sandstones and shales in the Santa Ines formation above a point about 2500 feet from the base of the formation on Quebrada Carapita and about 4000 feet above the base on the Rio Querecual. These are largely shallow-water marine or brackish-water forms. There is little stratigraphic variation in species throughout this great thickness of sediments and it seems evident that it was all deposited during a relatively short time interval. The following species have been identified:

Amiantis (*Lamelliconcha*) *acuticostatus* (Gabb)
Anadara sp. aff. *A. chiriquiensis* var. *bolivari* Weisbord (Pl. 8, figs. 1-2)
Cardita (*Glans*) sp. (Pl. 8, fig. 3)
Cardita (*Carditamera*) sp. (Pl. 8, fig. 7)
Cardium (*Trigonicardia*) sp.

[110] R. A. Liddle: *The geology of Venezuela and Trinidad* (1928). J. P. MacGowan, Fort Worth, Texas.

Clementia cf. *dariena* Conrad (Pl. 8, fig. 8)
Corbicula sp. (Pl. 8, fig. 17)
Corbula sp. (Pl. 8, fig. 4)
Dentalium sp.
Marginella sp.
Melongena colombiana Weisbord (Pl. 8, fig. 9)
Nuculana sp. cf. *N. quitanensis* (Olsson)
Pinna sp.
Polystira cf. *barretti* (Guppy) (Pl. 8, fig. 16)
Potamides bolivarensis Weisbord (Pl. 8, fig. 12)
Potamides ? *suprasulcatus* (Gabb) (Pl. 8, figs. 10, 11)
? *Potamides prismaticus* (Gabb) (Pl. 8, fig. 13)
Sheppardiconcha sp. (Pl. 8, figs. 14, 15)
Tagelus (*Mesopleura*) sp. aff. *T. subaequalis*
Tellina sp.

The assemblage is typically Miocene, and Middle Miocene age is suggested. There is a marked resemblance to the fauna from just east of Esperanza on the Carmen-Zambrano road in the Department of Bolivar in northern Colombia, from which Weisbord [111] described several species. Through the courtesy of J. O. Nomland of the Standard Oil Company of California and Bruce Clark of the University of California, the writer had access to a very large collection from this Colombian locality. Many species are identical or very similar to those from Venezuela, and these Colombian sediments appear to be of an age and environment closely comparable to that of the Santa Ines formation.

Only a preliminary examination has been made of the Foraminifera of this formation. Highly foraminiferal shales occur near the base of the formation on Rio Querecual. The assemblage here shows considerable affinity to that of the Carapita formation but carries *Planorbulinella* and other shallow-water forms unknown in the Carapita formation. The bluish- and greenish-gray shale interval about 1000 feet above the base of the formation on the Rio Querecual (Samples E-290 to E-301) is also foraminiferal, and the assemblage here is even more suggestive of shallow water and less closely related to the typical Carapita formation fauna. Both these shale intervals are actually the time equivalents of the upper part of the Carapita formation farther east and are stratigraphically below the Middle Miocene mollusk horizons in the Santa Ines formation. While this microfauna has not yet been worked in detail, the writer is inclined to believe that it is approximately of Lower Miocene age.

Foraminiferal shales from 3000 to 5000 feet above the base of the formation on Rio Querecual carry a small assemblage of shallow-water marine forms somewhat related to the assemblages near the base of the formation but entirely distinct from that of the Carapita formation. These Foraminifera are associated with poorly preserved mollusks mentioned above and further support the Middle Miocene age of this part of the formation.

Only a few brackish-water Foraminifera have thus far been found in the shales of the middle and upper portions of the Santa Ines formation.

Stratigraphic Relations: There is probably an angular unconformity between the Carapita formation and the Santa Ines formation on Quebrada Carapita. The lithologic change is abrupt and dips in the upper part of the Carapita formation are 70 degrees to the North while the dip of the basal sandstone and conglomerate of

[111] N. E. Weisbord: *Miocene Mollusca of northern Colombia*, Bull. Am. Paleont., vol. 14, no. 54 (1929) p. 66.

the Santa Ines formation is 75 degrees to the South. On the Rio Oregano 15 kilometers east of the Quebrada Carapita section, the basal Santa Ines sandstone is dipping 35 degrees to the South and apparently rests on vertical Carapita shale belonging to the middle zone of that formation. The evidence for unconformity here is quite conclusive.

Westward from Quebrada Carapita, however, there is little indication of angular change at the contact and, on the contrary, the Carapita shales grade laterally in this direction into sandstones of the Santa Ines formation. Successive sandstone beds are added to the base of the Santa Ines formation in this direction, and the contact with the Carapita formation shales descends steadily lower in the section. As a result both of structural deformation connected with the Capaya Z-flexure and this lateral change to sandstone, the Carapita shale pinches out only a few kilometers west of Capaya and the sandstones of the Santa Ines formation come in contact with those of the lower member of the Carapita formation. In the absence of the separating shale member it is not at present practicable to distinguish these units, especially since in a westerly direction both the Carapita sandstones and the sandstones of the lower Santa Ines become conglomeratic, with pebbles of black chert, yellowish chert, and gray quartzitic sandstone. Therefore, in the area southeast of Barcelona (Cerro Grande), the Santa Ines formation extends to the top of the Merecure formation and in its lower part is probably the time equivalent of the whole Carapita formation.

The Santa Ines formation is overlain unconformably by sediments of probable Upper Miocene or Pliocene age.

CORRELATION: The Santa Ines formation grades westward into a coarse conglomerate series southwest of Barcelona known as the El Pilar conglomerate. To the east it is known in outcrop as far as the Rio Oregano-Corozal area but beyond this locality is overlapped by younger sediments.

The formation of the type locality is approximately equivalent to the Brasso-Manzanilla group of Trinidad and the Socorro and Urumaco formations of the State of Falcon in western Venezuela. Stehlin's[113] "Zaraza serie" in the State of Guarico is probably equivalent to some part of the Santa Ines formation.

DISTINGUISHING FEATURES: The formation in general is distinguished by its characteristic grits and conglomerates, and its brackish and shallow-water marine mollusks and Foraminifera. Mineralogically, it is distinct from all formations older than the Carapita formation and differs from that formation in the more common occurrence of staurolite.

GEOLOGIC HISTORY

The development of the great Andean geosyncline of South America probably began at least as early as Cretaceous time. A broad, gently subsiding trough paralleled the western edge of the continent and at its north end bent eastward through Venezuela around the periphery of the Guayana or Brazilian shield to open into the Atlantic Ocean. This northeastern portion of the main geosynclinal belt has been termed the Venezuelan Geosyncline,[113] or, in its easternmost part, the Orinoco Geosyncline.[114] A

[113] H. G. Stehlin: *Ein Astrapotheriumfund aus Venezuela*, Eclogae geol. Helv., vol. 21, no. 1 (1928) p. 227-232.

[113] Charles Schuchert: *Historical geology of the Antillean Caribbean region*, (1935) p. 679. John Wiley and Sons, New York.

[114] R. A. Liddle: *op. cit.*, p. 364.

borderland, to which Guppy [115] has given the name Paria, probably lay to the north during much of Cretaceous and Tertiary time, but the position of this land (or lands) is extremely hypothetical. Its existence is

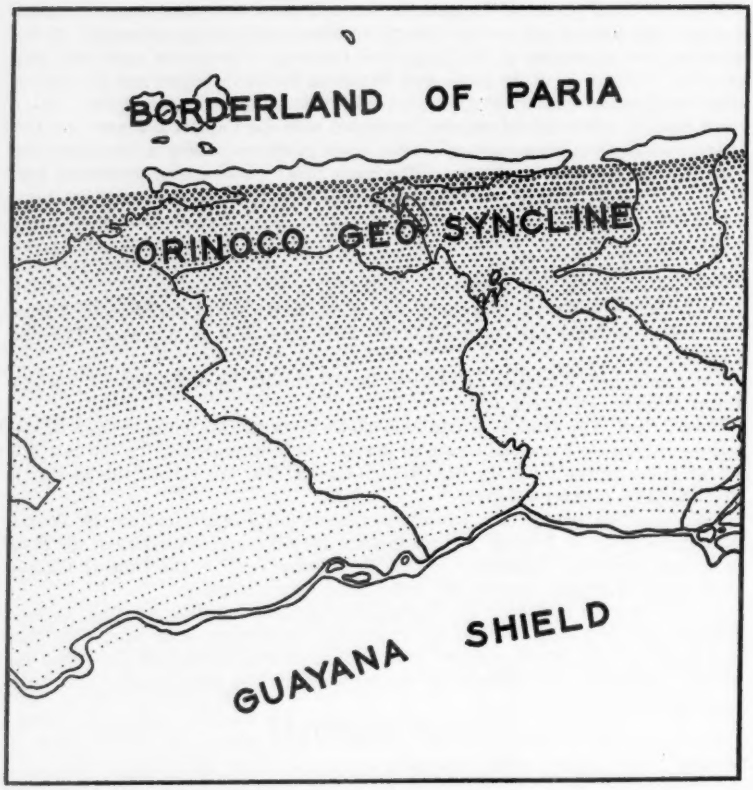

FIGURE 2.—*Sketch map of structural and paleogeographic elements in eastern Venezuela during Tertiary time*

based principally on the need for a source in this direction for much of the sedimentary filling of the geosynclinal trough. (The hypothetical positions of Paria and the Orinoco geosyncline during Tertiary time, with respect to the Guayana Shield, are shown on Figure 2.)

[115] R. J. L. Guppy: *On the geology of Antigua and other West Indian islands with reference to the physical history of the Caribbean region*, Geol. Soc. London, Quart. Jour., vol. 67 (1911) p. 681-700.

The geologic history of northeastern Venezuela since the beginning of the Cretaceous is in large part the history of the relative vertical movements of the Parian borderlands and the Orinoco geosyncline, and of the tangential forces acting between Paria and the Guayana shield. Sedimentation in this region, and in the Rio Querecual area in particular, may be divided into three major phases (Cretaceous, Upper Eocene, and Oligocene-Miocene) during each of which the cycle of events is conceived to have been somewhat as follows:

1. Gradual sinking of the broad trough between Paria and Guayana, with deposition in general keeping pace with subsidence so that shallow-water marine conditions prevailed. Principal axis of depression along the north margin of the basin.
2. Development of geosynclinal structure through continued subsidence with consequent weakening of the rigidity of the crust.
3. Yielding of the geosynclinal belt to pressure of the Parian borderland directed toward the Guayana shield. Relative southward movement of Paria with consequent buckling of the north border of the geosyncline and overthrusting toward the south.
4. Uplift and mountain making accompanying and following folding in the axial portion of the geosyncline. General retreat of the sea from the geosynclinal belt.
5. Erosion of uplifted sediments, isostatic readjustment, return of the sea to the geosyncline, and the initiation of a new cycle, but with the axis of subsidence shifted relatively farther to the south.

The initial deposits of the Cretaceous cycle in northeastern Venezuela are sandstones, varicolored shales, and oyster limestones of the Barranquin formation, laid down in, or at the borders of, a shallow transgressing sea which eventually advanced over the whole Andean geosynclinal belt. Great thicknesses of coarse sediments were dumped into the shallow waters of the subsiding trough from elevated borderlands and the character of Lower Cretaceous deposits throughout the whole of northern South America is dominantly clastic. De Cizancourt [116] refers to these sediments as a *flysch* facies.

By early Middle Cretaceous (Aptian-Albian) time the elevation of the bordering land areas had been reduced, less sediment was being brought in, and limestone deposition became important. The El Cantil, Capacho, Cogollo, and lower Villeta limestones of Venezuela and Colombia were formed and locally highly glauconitic facies such as that of the Bergantin beds were developed. The maximum Cretaceous transgression probably

[116] Henri de Cizancourt and M. D. Schneegans: *Introduction à la géologie du Venezuela et bibliographie géologique*, Annales de l'Office nationale de combustibles liquides, 11ième année, no. 1 (1936) p. 96.

occurred in the late Middle Cretaceous when the distinctive black, carbonaceous, and often bituminous, limestones of the Querecual, Guayuta, La Luna, and upper Villeta formations were deposited. In the deeper portions of the seaway, clastic sediment was at a minimum, and peculiar conditions, probably due to hindrances to the free circulation of the marine waters, resulted in the preservation of immense quantities of organic matter and pelagic Foraminifera on bottoms which were only rarely favorable for benthonic animal life.

Late in Cretaceous time the seaway began to shrink. Clastic sediment brought in by streams was now carried by currents to the deepest parts of the trough to form the sandstone lenses and channels which cut through the dark limestones of the San Antonio formation. Locally, thick sandstones like those of the lower part of the Santa Anita formation were formed. Deposition was in general slow, however, and during temporarily static conditions glauconite was concentrated on the sea floor. Benthonic Foraminifera as well as pelagic forms thrived locally. On sandy bottoms their tests were poorly preserved, as is the case in the San Antonio and Santa Anita formations, but mud bottoms allowed the accumulation of highly foraminiferal facies like that of the Colon shale of western Venezuela.

In the borderland areas, it is probable that this was a time of considerable volcanic activity. It is noteworthy that the Upper Cretaceous sediments of the Caribbean islands consist in large part of volcanic tuffs, submarine and subaerial flows, and clastic sediment derived from volcanic rocks; and on the Dutch islands of Curacao, Aruba, and Bonaire, just off the Venezuelan coast, the Upper Cretaceous includes 10,000 to 15,000 feet of diabases, tuffs, porphyrites, cherts, and radiolarites, with only a minor amount of limestone.[117] Volcanic materials of Cretaceous age have not yet been definitely identified in the sediments of the Venezuelan geosyncline but it may be that porous siliceous shales of the San Antonio and Santa Anita formations and the white porcellanites and tripolites of the Guadalupe and Santa Barbara formations of eastern Colombia and western Venezuela are at least in part made up of volcanic ash.

The close of Cretaceous time was marked by rather general emergence of land areas throughout the Caribbean region as a whole but within the troughs of the great Andean and Venezuelan geosynclines the extensive Cretaceous seas lingered on into Eocene time. The Caratas member of the Santa Anita formation appears to be a Cretaceous-Eocene transition deposit which finds its counterpart in western Venezuela in the Rio de Oro formation and in Colombia in the uppermost Umir and

[117] P. J. Pijpers: *Geology and paleontology of Bonaire (D. W. I.)*, Geog. Geol. Meded., Physiographische-Geologische Reeks, no. 8 (1933) 103 pages.

lowermost Lisama formations of Wheeler.[118] Sediments of this transition period were formed in shallow shifting seas and deposits of highly variable lithology were laid down. Conditions favorable for limestone deposition were widespread early in the Eocene when the "*Venericardia* limestones" of Cerro Corazon (eastern Venezuela), Soldado Rock, Trinidad, western Venezuela, and Colombia were deposited. Unfortunately, this limestone horizon cannot be definitely identified in the Rio Querecual section although it probably was formed late in or just following Santa Anita time.

The deposits of the Santa Anita formation mark the close of the first cycle in the history of the sediments of the Rio Querecual section. Although there is little direct evidence of unconformity, it is probable that following Santa Anita deposition there was complete emergence of the area and also folding of the sediments of the geosyncline. Lack of angular discordance in the Rio Querecual section at the top of the Santa Anita formation cannot be interpreted to mean that folding of the geosyncline did not occur at this time. In the cycle of events already outlined, it is to be supposed that folding accompanying the southward movement of Paria was concentrated along the axis of the geosyncline, immediately adjacent to the southern edge of the borderland and in the belt of heaviest sedimentation and greatest crustal weakness. Southward from the axis over the broad shallow southern limb of the basin, strata remained nearly horizontal or were sharply folded only locally along fault lines in the basement. With successive periods of movement the axis of the geosyncline has been steadily shifted southward until it now lies south of the Rio Querecual area, but in Eocene time the axis probably was a considerable distance to the north so that the effects of crustal disturbance in the Rio Querecual area were very mild. Similarly, an advance of the sea over the present area of the geosyncline would lay down marine deposits which in the area away from the immediate mountain front would have no measurable angular relation to Tertiary strata in spite of the tremendous disastrophism which is known to have occurred near the close of that period. Lehner[119] considers the first great tectonic movement recorded in Trinidad to have occurred between the Lower and Middle Eocene.

A second great marine transgression in the Caribbean region, following that of Cretaceous time, culminated in the late Eocene. The sea advanced far into the Venezuelan geosyncline, but the Rio Querecual

[118] O. C. Wheeler: *Tertiary stratigraphy of the middle Magdalena Valley*, in H. A. Pilsbry and A. A. Olsson: *Tertiary fresh-water mollusks of the Magdalena embayment, Colombia*, Philadelphia Acad. Nat. Sci., vol. 87 (1935) p. 21-39.

[119] E. Lehner: *Introduction à la géologie de Trinidad et bibliographie géologique*, Annales de l'Office nationale de combustibles liquides, no. 4 (1935) p. 704-705.

area apparently lay near its borders and the rather poorly known Merecure formation was deposited largely in shallow water near shore. To the west it grades into coarse clastics and non-marine coal swamp deposits while to the east somewhat deeper water marine conditions prevailed and in Trinidad the highly foraminiferal *"Hantkenina* marl" was deposited. Toward the close of Merecure time, conditions were favorable for limestone deposition, and orbitoid reef limestones, probably equivalent to horizons in the upper part of the Merecure formation, are known on Rio Unare, Rio Areo, Soldado Rock, and in Trinidad.

Diastrophism near the close of the Eocene in northern South America seems to have been widespread and violent, though of relatively short duration. The broad Venezuelan-Andean geosyncline was broken up into the smaller, narrower, Orinoco, Maracaibo-Falcon, and Magdalena basins by the uplift of the Eastern Cordillera of the Andes in Colombia and the Venezuelan Andes in Venezuela. Batholithic intrusions of granitic rocks occurred in both countries,[120] and Cretaceous and early Tertiary sediments were locally metamorphosed. Maury[121] has called attention to the twofold division of the Upper Eocene of Soldado Rock into Bartonian and Ludian equivalents. In northern Peru, Olsson[122] believes that a major unconformity occurs within the Upper Eocene sediments and Senn[123] has recently shown that in western Venezuela uppermost Upper Eocene strata rest with angular unconformity but are overlain conformably by Lower Oligocene strata. Schuchert[124] recognizes the probable importance of late Eocene orogeny in northern South America and refers particularly to evidence of disturbance at this time on the island of Barbados.

The Merecure formation probably belongs to the lower part of the Upper Eocene (Bartonian) but sufficient information is not yet available definitely to prove this point. The age of the lowest part of the overlying Carapita formation is not known so that the magnitude of any hiatus which may exist between Merecure and Carapita formations cannot be accurately determined. There is little direct evidence of unconformity but it seems probable that major orogeny occurred after the deposition of the Merecure formation and before Carapita time.

[120] H. M. E. Schürmann: *Massengesteine der venezolanischen Anden,* Neues Jahrb. Mineral., Geol., Paläont., Beil-Bd. 68, Abt. A (1934) p. 377-400.

[121] C. J. Maury: *Bartonian and Ludian upper Eocene in the western hemisphere,* Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 375-376.

[122] A. A. Olsson: *Contributions to the Tertiary paleontology of northern Peru, Part III, Eocene Mollusca,* Bull. Am. Paleont., vol. 17, no. 62 (1930) p. 8.

[123] Alfred Senn: *Die stratigraphische Verbreitung der Tertiaren Orbitoiden mit spezieller Berucksichtigung ihres Vorkommens in Nord-Venezuela und Nord-Marokko,* Eclogae geol. Helv., vol. 28, no. 1 (1935) p. 59-60.

[124] Charles Schuchert: *op. cit.,* p. 617-618.

The absence of angular relation in the Rio Querecual area may be explained as in the case of the Santa Anita and Merecure formations.

Regardless of the magnitude of the unconformity in the Rio Querecual area, it is evident that near the close of Merecure deposition a great change took place in the source of sediments being deposited in this region. All older rocks in the Querecual section show a very simple heavy mineral suite probably derived from the erosion of pre-existing sediments, but in the upper part of the Merecure formation are sporadic occurrences of garnet and chloritoid and in the overlying Carapita and Santa Ines formations these minerals are persistently present. Staurolite also becomes more common and glaucophane is occasionally present. It is probable that all these minerals are related either to metamorphism occurring during Upper Eocene orogeny or to the exposure to erosion at this time of metamorphic rocks formed in an earlier epoch.

The Carapita and Santa Ines formations belong to a single great Oligocene-Miocene cycle of deposition. Early in Oligocene time the sea began to advance from the east into the Orinoco geosyncline, which lay between the periphery of the Guayana shield and the newly formed mountains of the Carribean Range and Venezuelan Andes, and was more restricted in area than the original Venezuelan geosyncline. Lower Oligocene foraminiferal shales are known in Trinidad (lower part of Cipero silts), but marine deposition probably did not begin in the Rio Querecual area until somewhat later. Here the shallow-water, sandy sediments of the lower member of the Carapita formation constitute the initial deposits of the marine transgression. The Rio Querecual area at this time lay near the axis of the geosyncline and subsidence kept pace with deposition allowing the accumulation of immense thicknesses of sediment. The upper member of the Carapita formation was laid down in quiet and probably moderately deep water; Foraminifera indicate that at least the lower part of this member was formed in Upper Oligocene time. Although lithologic character and fossil fauna both suggest fairly deep water, the Rio Querecual area must have been rather near shore during this time since only a few kilometers farther west the whole of the Carapita formation grades laterally into coarse clastics. These cannot be differentiated lithologically from the Santa Ines formation which overlies the Carapita formation in its type section.

In early Miocene time the sea again became more shallow, and the sandy facies which had been deposited farther west through Carapita time began to encroach on the Rio Querecual area (lower part of Santa Ines formation of Rio Querecual section). By Middle Miocene time the Santa Ines formation conglomerates, sands, and sandy muds of brackish- and shallow-water marine origin had completely replaced the finer de-

posits of the Carapita formation. For the most part, the two formations seem to be intergradational both laterally and vertically. For this reason the angular relation and sharp contact between them on Quebrada Carapita and Rio Oregano is difficult to explain although it is probably associated with the position of the area in the structurally mobile axial portion of the basin.

Rapid shallow-water marine and brackish-water deposition continued throughout Middle Miocene time, forming the immense thickness of dominantly clastic sediments which constitute the type Santa Ines formation. With regard to northeastern Venezuela as a whole, the Santa Ines and Carapita formations may probably be considered merely as facies differentiates in a single cycle of deposition. The development of the Santa Ines formation (shallow-water facies) increases to the west, and the development of the Carapita formation (deep-water facies) increases to the east. In the Rio Querecual area the two together represent at a minimum the deposits from Upper Oligocene to Middle Miocene time inclusive, and are comparable in age and scope to the Brasso-Manzanilla group of Trinidad and the Agua Salada group of eastern Falcon.

Early in Upper Miocene time there was renewed crustal movement followed by the deposition of Upper Miocene and Pliocene sediments. These have been entirely removed from the area of the Rio Querecual section but overlap the Santa Ines formation with slight angular unconformity farther south.

From Oligocene to Pliocene time the Orinoco geosyncline had been the site of almost continuous deposition, interrupted only by relatively minor uplifts. A tremendous thickness of sediments had accumulated, representing in the Rio Querecual area a subsidence of at least 4 or 5 miles. In Middle Pliocene time, however, deposition was interrupted by the so-called Antillean Revolution, a crustal disturbance as great or greater than any which had affected the region since the Paleozoic era. The Parian borderland was again pushed southward toward Guayana, the shallow waters retreated from the area of the intervening trough, the north border of the geosyncline was again folded, overturned, and overthrusted from the north; and the crumpled mass of sediments was uplifted to form the Serrania del Interior. During the readjustment accompanying or following this orogeny, the greater part of the Parian borderland was dropped below the level of the sea by a relaxational movement along the great fault line defining the northern coast lines of Venezuela and Trinidad. (Another great fault line passes through the Gulfs of Cariacou and Paria and separates the metamorphic rocks of the Serrania de la Costa from the sediments of the Serrania del Interior.) Evi-

dence of this part of the former borderland is seen today only in the shallow water extending northward from the present coast and in the protruding remnants of Parian topography represented on the islands of Orchila, Blanquilla, Margarita, Cubagua, Los Testigos, Tobago, and perhaps Barbados.

The Rio Querecual area was very near the axis of the geosyncline during Oligocene-Miocene deposition and it was accordingly nearer the area of greatest disturbance during the Pliocene Revolution than in previous orogenies. Tertiary and older strata were highly folded, overturned, and otherwise deformed; then uplifted and deeply eroded. An immense volume of rock was stripped away and spread out over the basin to the south and east to form the great Venezuelan Mesa. By early Quaternary time elevation of the land had been reduced to such an extent that these alluvial deposits encroached on the Rio Querecual area, and coarse boulder deposits, laterally continuous with the finer sediments of the Mesa farther south, were strewn across the truncated edges of older strata. Late Pleistocene or Recent uplift, however, has rejuvenated the streams and erosion is still the dominant process over the whole area.

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Explanation of Plate

Explanation of Plate 8

Figures 1, 2. *Anadara* sp: aff. *A. chiriquiensis* var. *bolivari* (Weisbord). Sample E-4066, near Santa Ines. Figure 1: height of specimen 27 mm., length 35 mm., thickness (half) 15 mm.; a, interior right valve; b, exterior right valve. Figure 2: left valve of another specimen; height 17 mm., length 22 mm.

The Venezuelan specimens closely resemble some of the forms included in Weisbord's variety *bolivari* from the Middle Miocene of Colombia [Bull. Am. Paleont., vol. 14, no. 54 (1929) p. 8, pl. 1, figs. 4-9]. They are particularly close to the extremes represented by Weisbord's figures 8 and 9 but lack the faint sinus shown by these Colombian forms. There is great variation in both Venezuelan and Colombian specimens and those from Venezuela show little resemblance to Weisbord's figures 4 to 7, which have a pronounced sinus.

Figure 3. *Cardita (Glans)* sp.; left valve; height 10 mm., length 11 mm., thickness 8.5 mm. Sample E-246, Rio Querecual, south of Capaya.

Figure 4. *Corbula* sp.; right valve; height 11.5 mm., length 15 mm., thickness 8.5 mm. Sample E-195, near Santa Ines.

Figure 5. *Tellina* sp.; left valve; height 11.5 mm., length 19 mm. Sample E-248 on Rio Querecual south of Capaya.

Figure 6. *Mytilus* sp.; right valve of worn specimen; height 12 mm., length 26 mm. Sample E-195, near Santa Ines.

Figure 7. *Cardita (Carditamera)* sp.; right valve; height 13 mm., length 24 mm. Sample E-4176, near Santa Ines.

Figure 8. *Clementia* cf. *dariena* Conrad. Immature specimen; distance from beak to opposite end 18 mm. Sample E-248, Rio Querecual south of Capaya.

Figure 9. *Melongena colombiana* Weisbord. Sample E-3290 (south of area of map, Plate 1). a side view; b, end view; height 84 mm., diameter 69 mm.

This species was originally described by Weisbord from the Miocene of northern Colombia [Bull. Am. Paleont., vol. 14, no. 54 (1929) p. 43, pl. 7, figs. 2-4]. It was later also identified by Olsson in the Zorritos group of the Lower Miocene of Peru [Bull. Am. Paleont., vol. 19, no. 68 (1932) p. 177, pl. 19, fig. 1]. Examination of many specimens from Colombia and Venezuela shows great variation in size and arrangement of spines.

Figures 10, 11. *Potamides (?) suprasulcatus* (Gabb). Sample E-195, near Santa Ines. Figure 10: length, 34 mm., diameter, 19 mm. Figure 11: length of longer specimen 35 mm.

This species, very common in the Santa Ines formation, was originally described by Gabb from Santo Domingo as *Cerithium suprasulcatum* [Am. Phil. Soc., Tr., vol. 15 (1873) p. 236]. Gabb's description, however, is of an eroded specimen. Two specimens from the original Gabb collection, one worn and the other with ornamentation preserved, were later figured by Pilsbry who changed the generic name to *Potamides* [Philadelphia Acad. Nat. Sci., Pr., vol. 73 (1921) p. 373, pl. 29, figs. 10, 11]. Worn specimens like Pilsbry's figure 11 are common in the Venezuelan material and such a specimen evidently was the basis for Gabb's original description.

In 1917 Maury described a well-preserved specimen of the same species in the Gabb collection and named it *Potamides ormei* [Bull. Am. Paleont., vol. 5, no. 29 (1917) p. 126, pl. 22, fig. 8]. Spieker identified this species in the Zorritos group in Peru and named a variety *P. ormei infraliratus* [Johns Hopkins Univ., Studies in Geol., no. 3 (1922) p. 58, pl. 2, fig. 11]. Olsson raised Spieker's variety to species rank [Bull. Am. Paleont., vol. 19, no. 68 (1932) p. 193, pl. 23, figs. 5, 12]. Weisbord identified *P. ormei* in Miocene deposits of northern Colombia [Bull. Am. Paleont., vol. 14, no. 54 (1929) p. 38, pl. 8, figs. 6, 7,]. Examination of abundant material from Venezuela and Colombia, as well as Gabb's original specimens from Santo Domingo and Olsson's and Maury's types from Peru and Santo Domingo has convinced the writer that these should all be assigned to Gabb's species *suprasulcatus*. The correct genus name is questionable.

Figure 12. *Potamides bolivarensis* Weisbord. Length 29 mm., diameter 17 mm. Sample E-4176, near Santa Ines.

The Venezuelan specimens are smaller than Weisbord's type from the Miocene of Colombia [Bull. Am. Paleont., vol. 14, no. 54 (1929) p. 39, pl. 8, fig. 5]. As noted by Weisbord, the species closely resembles *P. dentilabris* (Gabb) from Santo Domingo as described by Pilsbry [Philadelphia Acad. Nat. Sci., Pr., vol. 73, pt. 2 (1921) p. 374, pl. 29, figs. 6, 7], and may be synonymous.

Figure 13. *? Potamides prismaticus* (Gabb). Length 35 mm., diameter 18 mm. Sample E-4176, near Santa Ines.

The Venezuelan specimens are very close to Gabb's species as figured by Pilsbry from the Miocene of Santo Domingo [Philadelphia Acad. Nat. Sci., Pr., vol. 73, pt. 2 (1921) p. 373, pl. 29, fig. 12], but the identity is not certain because of the impossibility of checking the presence of a strong spiral on the columella of the few specimens available from Venezuela.

Figures 14, 15. *Sheppardiconcha* sp. Sample E-195, near Santa Ines. Figure 14: length 25 mm., diameter 8.5 mm. Figure 15: length 20 mm., diameter 10 mm.

The genotype, *S. bibliana* Marshall and Bowles, was described from fresh-water deposits at Biblian, Ecuador, of an age "not later than Pliocene" [U. S. Nat. Mus., Pr., vol. 82, pt. 5 (1932) p. 3, pl. 1, fig. 6]. Specimens from the Santa Ines formation are very similar but have slightly more numerous spirals and more prominent nodes.

Figure 16. *Polystira* cf. *barrettii* (Guppy). Length 30 mm., diameter 9 mm. Sample E-246, Rio Querecual south of Capaya.

Figure 17. *Corbicula* sp. Limestone in Santa Ines formation on Quebrada Leon just east of Santa Ines, Sample E-4148.

MOLLUSCAN FOSSILS FROM THE SANTA INES FORMATION

Section A

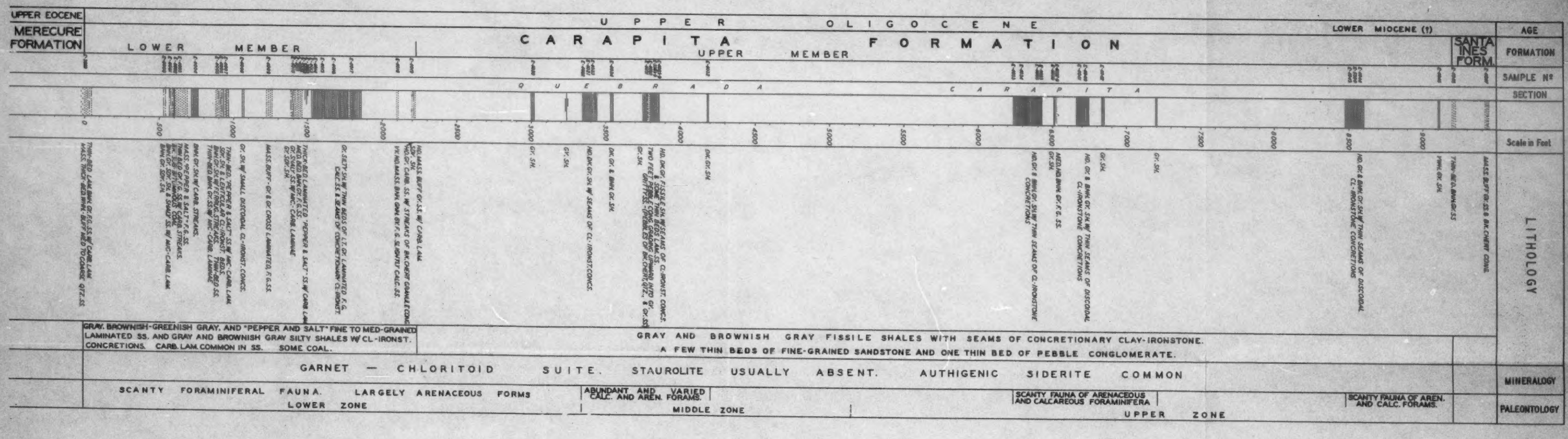
AGE	FORMATION	SAMPLE Nº	SECTION	Scale in Feet	LITHOLOGY	MINERALOGY	PALEONTOLOGY
MIDDLE CRETACEOUS	"BERGANTIN BEDS"				THICK-BEDDED MASSIVE, HARD, WHITE OR BUFF QUARTZITIC SANDSTONES SEPARATED BY INTERVALS WHICH ARE LARGELY COVERED BUT PROBABLY CONSIST OF SHALE AND SANDY SHALE.		
UPPER CRETACEOUS	QUEREGUAL FORMATION		QUEREGUAL SECTION		HARD BLACK THIN-BEDDED AND LAMINATED CARBONACEOUS LIMESTONE LAYERY CALCAREOUS SHALE, WITH DISCOIDAL LIMESTONE CONCRETIONS	ABUNDANT PELAGIC FORAMINIFERA.	COMMON PELAGIC FORAMINIFERA AND SOME BENTHONIC FORAMS.
	SAN ANTONIO FORMATION				HD. BK. THIN-BEDDED CARB. LIMEST. & CALC. SH. ALTERNATING WITH BEDS OF HD. LIGHT GRAY CALC. SANDSTONE	SIMPLE ZIRCON-LEUCOXENE SUITE	
	STA ANITA FORM.						

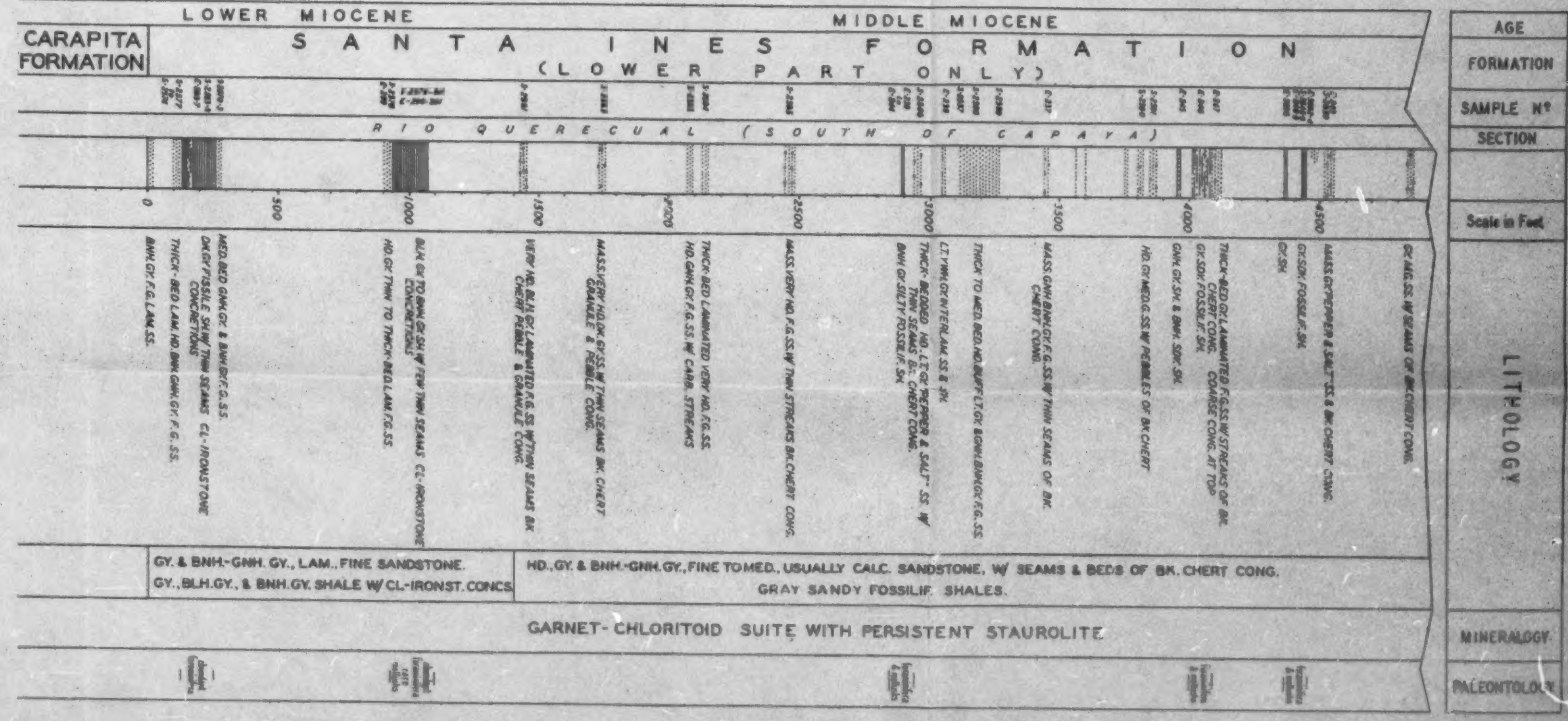
Section B

AGE	FORMATION	SAMPLE Nº	SECTION	Scale in Feet	LITHOLOGY	MINERALOGY	PALEONTOLOGY
UPPER CRETACEOUS — PALEOCENE	SANTA ANITA FORMATION, CARATAS MEMBER		RIO QUEREGUAL SECTION		MASSIVE BLUISH GRAY FOSSILIFEROUS LIMESTONES AND COARSE LIGHT-COLORED, LOCALLY GLAUCONITIC SANDSTONES (COVERED INTERVALS ARE PROBABLY SHALE)		
	SAN ANTONIO FORM.				SIMPLE ZIRCON-LEUCOXENE DETRITAL MINERAL SUITE AUTHIGENIC GLAUCONITE LOCALLY COMMON		
					POORLY PRESERVED MOLLUSKS IN LIMESTONES	ORBITOLINA CONCAVA VAR TEXANA (DOCEMES?)	
UPPER EOCENE	LOS MILLOS SANDSTONE						
	MERCURE FORMATION		QUEBRADA MERCURE SECTION		MASSIVE HARD WHITE OR BUFF QUARTZITIC SANDSTONES SEPARATED BY INTERVALS WHICH ARE LARGELY COVERED BUT PROBABLY CONSIST OF SHALE AND SANDY SHALE.		APPARENTLY BARREN OF FOSSILS
OLIG.	CARAPITA FORM.		QUEBRADA CARAPITA SECTION			SUITE	

ZIRCON - LEUCOXENE DETRITAL MINERAL SUITE

SIMPLE


UPPER EOCENE
MERECURE FORMATION
LOWER MEMBER
UPPER OLIGOCENE
CARAPITA FORMATION
UPPER MEMBER
LOWER MIOCENE (?)
SANTA INES FORM.
AGE
FORMATION
SAMPLE Nº
SECTION
Scale in Feet
LITHOLOGY
GRAY, BROWNISH-GREENISH GRAY, AND "PEPPER AND SALT" FINE TO MED-GRAINED LAMINATED SS. AND GRAY AND BROWNISH GRAY SILTY SHALES W/ CL-IRONST. CONCRETIONS. CARB. LAM. COMMON IN SS. SOME COAL.
GRAY AND BROWNISH GRAY FISSILE SHALES WITH SEAMS OF CONCRETIONARY CLAY-IRONSTONE. A FEW THIN BEDS OF FINE-GRAINED SANDSTONE AND ONE THIN BED OF PEBBLE CONGLOMERATE.
GARNET — CHLORITOID SUITE. STAUROLITE USUALLY ABSENT. AUTHIGENIC SIDERITE COMMON
MINERALOGY
SCANTY FORAMINIFERAL FAUNA. LARGELY ARENACEOUS FORMS
LOWER ZONE
ABUNDANT AND VARIED CALC. AND AREN. FORAMS.
MIDDLE ZONE
SCANTY FAUNA OF ARENACEOUS AND CALCAREOUS FORAMINIFERA
SCANTY FAUNA OF AREN. AND CALC. FORAMS.
UPPER ZONE
PALEONTOLOGY



GRAPHIC COLUMNAR SECTIONS

HEDBERG, PL.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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ILLUSTRATIONS

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1. Map showing epicenters and the contour at depth 31 km. of the Sierra root. 2026
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VOLUME 47

The Sierra Nevada in the Light of Isostasy. By Andrew C. Lawson

(pages 1691-1712)

Comment by PERRY BYERLY

In the November (1936) number of this journal A. C. Lawson[1] concluded from isostatic considerations that the granitic mass of the Sierra in the vicinity of Mount Whitney is of a thickness about 68 km., its base extending down some 19 km. into the ultra basic rock of the earth's mantle. He has asked me to point out certain seismometric data that tend to confirm the great depth of penetration of the mountain mass.

[1] A. C. Lawson: *The Sierra Nevada in the light of isostasy*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 1691-1712.

A study of the Eureka (California) earthquake [2] of June 6, 1932 first indicated that the P_n wave of the seismologist, when it originates in northern California, is delayed in its arrival at the Owens Valley seis-

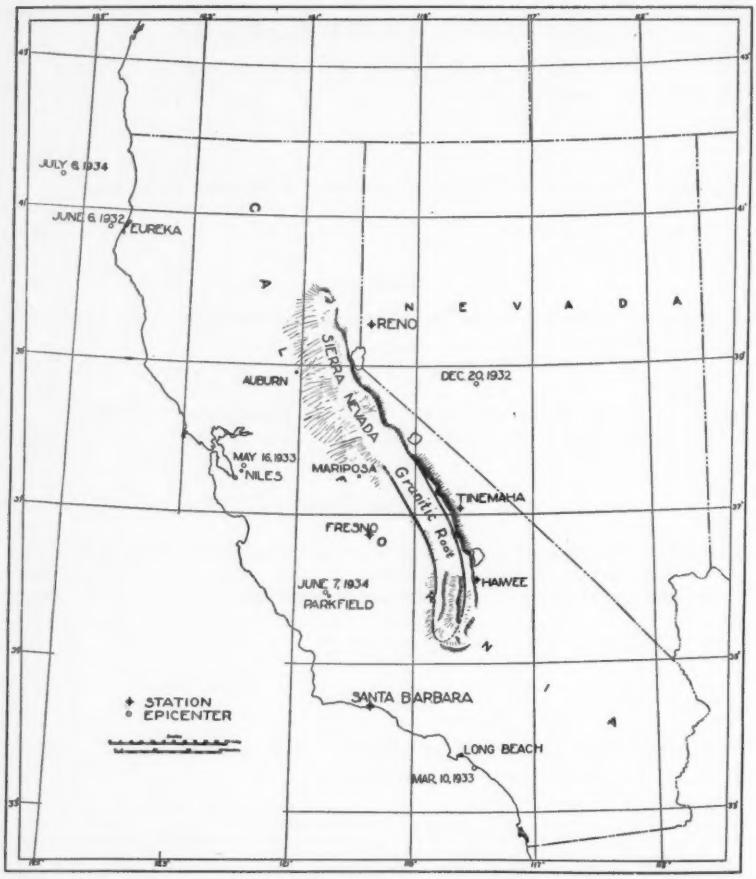

FIGURE 1.—*Map showing epicenters and the contour at depth 31 km. of the Sierra root*

mographic station of Tinemaha. The P_n wave is a first preliminary (compression-rarefaction) wave which travels in the ultra basic rock below the layered crust of the earth. The epicenter of this earthquake

[2] Perry Byerly and Neil R. Sparks: *The first preliminary waves of the California earthquake of June 6, 1932*, Am. Geophys. Union, Tr., 14th Ann. Meeting (1933) p. 254-256.

was just off Humboldt Bay at 124°30′ west longitude, 40°45′ north latitude. It is plotted on Figure 1. P_n was delayed about 4.5 seconds in its arrival at Tinemaha for this shock. In the paper cited the interpretation was made that P_n failed to record, but that a later wave group was the first registered. There were no seismograms for this earthquake from Haiwee, the other Owens Valley station.

In the study of the Niles earthquake [3] of May 16, 1933, epicenter at 37°38′ N, 121°57′ W (near San Francisco Bay), it was found that the P_n waves from this epicenter were delayed about three seconds in their arrival at Tinemaha and Haiwee. In the same paper it was shown that the P_n waves of the Parkfield earthquakes were delayed two seconds in travelling to these two stations. The Parkfield shocks centered on the San Andreas Fault near the southern boundary of Monterey County at 35°56′ N, 120°29′ W. It was suggested in the discussion of these shocks that these delays were due to the Sierra or the Great Valley.

A study of the earthquake [4] of July 6, 1934 showed that P_n waves from this epicenter, 41°36′ N, 124°30′ W, were delayed 4.3 seconds in their arrival at Tinemaha, and 6.6 seconds in their arrival at Haiwee. An investigation of the earthquake of February 7, 1937 has just been completed. The epicenter of this shock was at 40°27′ N, 125°35′ W, again off the coast of Humboldt County. This shock shows the customary lag, four seconds in reaching Tinemaha. There is no detectable lag in the arrival at the Fresno station which was established early in 1936 and is in charge of W. M. Tucker, of the Fresno State College. The station was therefore not in operation at the time of the earlier shocks. For testing the lag at Fresno, as at the Owens Valley stations, there are needed more coastal California epicenters which may be determined accurately without the use of these stations. Although few are available since the establishment of the Fresno station, they seem to indicate that the lag is accumulated east of Fresno; i.e., under the Sierra.

According to the identifications made in the paper cited $\overline{P}$, the wave in the upper or "granitic" layer, was on time at Tinemaha and Haiwee for the Parkfield and Niles earthquakes. This is in agreement with the idea of the existence of a granitic root under the Sierra. Theoretically, such a root should cause no delay of $\overline{P}$ but slight delays of the waves travelling in lower layers, the greatest delay being for P_n. The identification of other P waves (intermediate between P_n and $\overline{P}$) with particular layers is not very certain. There is no general agreement among investigators as to the exact partitioning of the crustal layers. There-

[3] Perry Byerly and James T. Wilson: *The central California earthquakes of May 16, 1933 and June 7, 1934*, Seism. Soc. Am. Bull., vol. 25 (1935) p. 223-246.

[4] Perry Byerly: *Earthquakes off the coast of northern California*, Seism. Soc. Am. Bull., vol. 27 (1937) p. 73-96.

fore, whether or not waves from the two intermediate layers below the granite are on time at Tinemaha and Haiwee seems to offer no good test as to the existence of a deep granitic root—i.e., as the identification of such waves is uncertain, no late wave would ever be assigned to one of them; it would automatically be grouped with a wave due later.

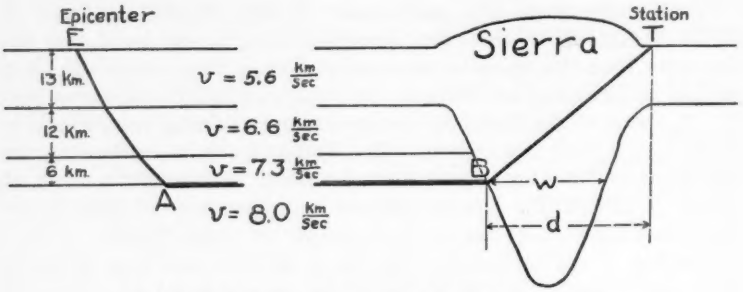

FIGURE 2.—*Idealized cross section through the Sierra*
Showing granitic root.

The earthquakes centering near Eureka are too far from the Owens Valley stations for a good $\overline{P}$ to be expected.

The study of the Nevada earthquake [5] of December 20, 1932, epicenter at 38°48′ N, 117°59′ W, showed no lag of P_n at Tinemaha or Haiwee. This indicates that the lag observed for the other shocks was due to a screening effect west of the stations. However, for this shock there was no lag in the arrival of P_n at Santa Barbara, the path to which lay across California and under the Sierra. Furthermore, the travel times of P_n for the Long Beach earthquake [6] showed no appreciable lag in reaching Tinemaha and Haiwee. Such waves need not pass under the Sierra.

The conclusions of Lawson regarding the very deep penetration of the Sierran granites in the region of Mount Whitney offer a good explanation of the delays in the travel times of P_n. In Figure 2 is shown an idealized cross section through the Sierra along a line joining Parkfield and Tinemaha or Haiwee. Such lines are approximately transverse to the trend of the range. The wave P_n travelling along EAB strikes granite at B and is diffracted to T through the granite, and thus its time is increased over that along a normal path which in its rise to the surface would have been symmetrical to the descent EA.

[5] Perry Byerly: *The first preliminary waves of the Nevada earthquake of December 20, 1932*, Seism. Soc. Am. Bull., vol. 25 (1935) p. 62-80.

[6] Beno Gutenberg: *The propagation of the longitudinal waves produced by the Long Beach earthquake*, Gerlands Beiträge zur Geophysik, vol. 41 (1934) p. 114-120.

Where the P wave enters the granite root, irregularity in the root face may allow the path as drawn in the figure to be in accordance with Snell's Law, or the P which reaches the station through the granite may be due to diffraction. The weakness of P at the Owens Valley stations in the case of Eureka shocks may indicate the latter. Only stations in the lee of the batholith would be in the shadow for the normal P_n. Stations at greater distances would show no delay, as the waves could pass under the downward protuberance. Such was the case for the Tucson recording of the Eureka earthquake of July 6, 1934 and the Santa Barbara recording of the Nevada shock of December 20, 1932.

The distance d as shown in the figure may be computed independently from the data of the Parkfield, Niles, and Eureka shocks. I shall assume as the normal structure for the region that found in the study of the Parkfield shocks (Fig. 2). This involves a thickness of 31 km. for the surface layers. Lawson's thickness was greater than this. Use of his thickness or some other (such as Gutenberg's for southern California) would lead to somewhat different numerical results but would not affect the general solution of the problem.

For the Parkfield shocks the travel time of the P_n wave for a near surface focus was given as $t_{P_n} = \frac{\Delta}{8.0} + 6.0$ (seconds) where Δ is the epicentral distance in kilometers. For a wave originating at the bottom of the surface layers, say directly under E, the normal travel time would be

$$t = \frac{\Delta}{8.0} + 3$$

Consider now the wave arriving at B. If the structure remained normal under the mountain, the time from B to T would have been

$$t_1 = \frac{d}{8.0} + 3$$

However, the time taken through the granite along the path BT is

$$t_2 = \frac{BT}{5.6} = \frac{\sqrt{d^2 + 31^2}}{5.6}$$

The lag observed is then

$$L = t_2 - t_1 = \frac{\sqrt{d^2 + 31^2}}{5.6} - \frac{d}{8.0} - 3$$

For the Parkfield shocks the lag was 2 seconds. Substituting 2 for L we find

$$d = 72 \text{ km.}$$

This value holds in the region of either Tinemaha or Haiwee.

For the Niles earthquake the great circle joining the epicenter and Tine-

maha makes an angle of 44° with that joining Parkfield and Tinemaha. For this case the lag

$$L = \frac{\sqrt{d^2 \sec^2 44° + 31^2}}{5.6} - \frac{d \sec 44°}{8.0} - 3$$

The lag was 3 seconds. Substituting 3 for L we get

$$d = 68 \text{ km.}$$

A more elaborate solution takes account of the bending of the ray in its horizontal projection at its incidence on the granitic root. The difference in speeds in the two media requires this. This solution results in ponderous equations which have been solved graphically and give $d = 68.5$.

Next, d may be computed from the lag of P_n from the northern California shocks at Tinemaha. These lags observed all lie between 4 and 4.5 seconds. The best determined [7] seems to be that of 4.3 for the shock of July 6, 1934. For waves from the focus of this shock and others near it, the least times path will be down the western side of the root at near grazing incidence with refraction into the root to Tinemaha at an angle approximately

$$d = \sin^{-1} \frac{5.6}{8.0} = 45°$$

It will be assumed that the root wall is vertical and that this angle is in the horizontal plane, the upper propagation being due to diffraction. Alternately, it might be assumed that the root surface is so irregular that a surface is offered such that a Snell's Law path directly to the station is possible. The difference in the computed d is only a few kilometers for the two cases.

Taking the origin at Tinemaha, the x axis N 35° W roughly parallel to the Sierra and the y axis perpendicular to it in the surface, let the co-ordinates of the July 6, 1934 shock be a, b, and the co-ordinates of the point where the ray is refracted at the granite boundary as x, y. Then the travel time of the P wave from a focus 31 km. deep would be

$$t = \frac{\sqrt{x^2 + y^2 + 31^2}}{5.6} + \frac{\sqrt{(a - x)^2 + (b - y)^2}}{8.0}$$

The travel time of a P wave in "normal" structure would have been

$$t^* = \frac{\sqrt{a^2 + b^2}}{8.0} + 3$$

and the lag the difference between these

$$L = t - t^*$$

[7] The lags at Haiwee for these shocks are less consistent. For two there were no observations, but for two they were +0.6 and +3 respectively.

If the angle of refraction into the granite is 45° as before, $x = y = d$. Moreover, $a = 751$ and $b = 213$. Substituting and solving

$$d = 64 \text{ km.}$$

Thus we see that shocks from Parkfield, Niles, and Eureka, all indicate a value of d of about 70 kilometers.

A more interesting distance geologically perhaps is w the breadth of the batholith at the bottom of the surface layers. If we may assume the batholith is symmetrical, and take its western surface expression at 100 km. west of Tinemaha, we have

$$w + 2(d - w) = 100$$

Put $d = 70$

$$w = 40 \text{ km.}$$

Perhaps the root should be expected to be steeper on its eastern flank. If it is vertical there, the thickness of the root at 30 km. depth would approach 70 km.

Regarding the northern limit of the root we cannot say as yet. For the Niles earthquake the Reno record indicated no lag. This suggests that the root does not extend so far north. But more records with accurate time are necessary before it can be said definitely that Reno is not shielded as are the Owens Valley stations.

SUMMARY

Lawson's conclusions as to a deep downward protuberance of the granitic mass of the Sierra Nevada in the vicinity of Mount Whitney is supported by seismometric data. The lag of the first arriving waves at the Owens Valley seismographic stations, when the source of such waves is in northern or central California, suggests that these stations are in the "shadow" of the batholith. Waves from the great Nevada shock and from the Long Beach shock arrived on time at these stations, showing that the screening effect is to the northwest and west. Waves to Tucson for northern California shocks are not delayed, nor are waves to Santa Barbara from Nevada shocks. But the stations in these cases are not closely in the lee of the mountain mass—waves can pass under its root to these observatories.

The seismometric data indicate that the root is about 40 to 70 km. broad in the direction transverse to the range at a depth corresponding to the bottom of the normal surface layering (about 30 km.).

Martinsburg limestones in Eastern Pennsylvania. By Ralph L. Miller
(pages 93-112)

Comment by GEORGE W. STOSE *

The detailed description of the limestone areas within the Martinsburg shale and the discussion of their lithology and position in the section is a valuable contribution to the subject. I am in accord, or have no observations that conflict, with most of the conclusions reached by the author, but I wish to present some points of difference.

Miller states (p. 100) that the limestone inliers of the western region "are interpreted [by him] as lenses of limestone deposited at different times subsequent to the deposition of the oldest Martinsburg shale," and in his general summary and conclusions (p. 111) he says: "The Martinsburg limestones are lenticular, of restricted extent, and are found at different horizons. In general, they are most abundant in the lower part of the formation. Limestone areas in the northern part of the shale belt may represent reappearance of the lower part of the formation by anticlinal uplift." With these conclusions I am in general agreement. We differ chiefly in that Miller regards the limestones at or near the base of the Martinsburg shale as lenses in that formation and calls them Martinsburg limestones, whereas I consider the limestones and interbedded shales at the base of the Martinsburg to be a separate formation, which I correlate with similar beds (cement rock) that lie at the base of the Martinsburg shale in the valley and have been named the Leesport limestone. It is well known that the limestone beds of the Leesport vary greatly along the strike in thickness and character and in the amount of interbedded shale, and similar, or even greater, variations across the strike are to be expected. In my opinion, it is warranted to regard tentatively as Leesport all interbedded limestones and shales that are known to be at the base of the Martinsburg, whether they occur at the southeast margin of the formation, or are brought up on anticlines within it, unless fossils establish that they are not equivalent, or the lithology is markedly different. It is granted that some of the limestone inliers have not been proved to be at the base, and therefore a reasonable doubt exists as to whether they are Leesport or limestone lentils within the Martinsburg. There can be, therefore, no criticism of Miller for being conservative and regarding such inliers as limestone lentils or beds in the Martinsburg until they are proved by fossils, structure, or stratigraphy to be at the base.

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I differ with B. L. Miller [1] and C. H. Behre [2] in the mapping of the massive-limestone outcrops near Seemsville, north of Allentown, as small inliers in the shale. This mapping is accepted by Ralph Miller (p. 108), and he states (p. 109) that "they are interpreted as lenses deposited in

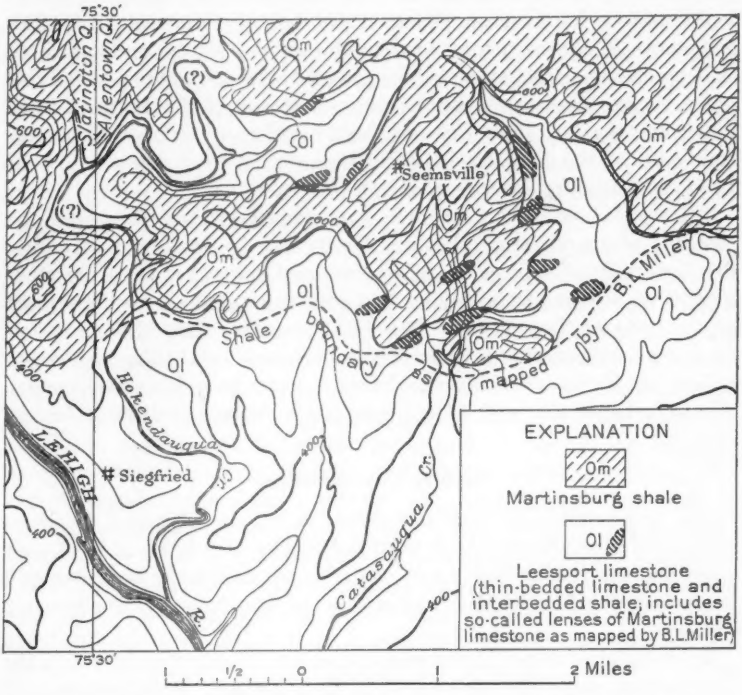

FIGURE 3.—*Geologic map of the vicinity of Seemsville, Pennsylvania*

Showing mapping of the base of the Martinsburg shale by the writer. The base of the Martinsburg shale as mapped by B. L. Miller is indicated by the heavy dashed line, and the small inliers (of dense pattern) were regarded by him as limestone lenses within the shale.

local areas of the dominantly muddy Martinsburg sea." Most of these so-called lenses are merely local exposures of hard rock that are favorable for quarrying, and they are surrounded by lowlands in which there are no exposures but which appear to be underlain also by limestone. A study of the field relations establishes the fact that this massive limestone lies below the main body of Martinsburg shale and that the small mapped areas south and east of Seemsville are parts of large limestone

[1] B. L. Miller: *Mineral resources of the Allentown quadrangle, Pennsylvania*, Pa. Geol. Survey, Topog. and Geol. Atlas, no. 206 (1925) p. 130.

[2] C. H. Behre: *Slate in Pennsylvania*, Pa. Geol. Survey, Bull. M-9 (1927) p. 21-23.

embayments, or re-entrants, of the main body of Leesport limestone to the south (Fig. 3). Similarly, three small "inliers" mapped by B. L. Miller west of Seemsville are interpreted by me as parts of a larger area underlain by limestone. However, this area and the small one in Catasauqua Valley are surrounded by Martinsburg shale and are therefore true limestone inliers, exposed within the shale by the erosion of minor anticlines. Similar structures have produced the irregular outlines of the embayments of the limestone-shale contact to the south, already referred to. I regard these limestones as the upper beds of the Leesport limestone, and the fact that they are thicker and more dolomitic than the main part of the Leesport indicates that during their deposition there was locally less argillaceous matter in the sea.

The *cryptozoon*-bearing layers in these limestones that I have seen are probably of organic origin, but this *Cryptozoon* is not the type found in the Conococheague limestone elsewhere, and I agree with Miller that there is no warrant for assigning an Upper Cambrian age to these rocks on the basis of these fossils. It is to be regretted that Miller presents no faunal evidence for his conclusions. It may be that none was obtained, but in the fuller paper to follow, referred to in his present paper, it is to be hoped that such faunal data as are available will be presented.

Reply by RALPH L. MILLER

The writer welcomes Stose's contribution on the subject of the limestones within the Martinsburg shale belt. The area involved is of such scope and complexity that the co-operative work of many geologists will be necessary before all the problems of the Martinsburg formation are unraveled.

In the original paper it was stated that the limestone areas within the Martinsburg shale belt were not all of the same age. Beekmantown and "Leesport" inliers were recognized, but the large majority of the limestones were interpreted as lenses at different horizons within the Martinsburg. Each area must therefore be classified individually, and neither Stose nor the writer is attempting to make a blanket designation covering all the limestones.

In the western region, disagreement exists largely on two counts. (1) Stose states that he believes "it is warranted to regard tentatively as Leesport all interbedded limestones and shales that are known to be at the base of the Martinsburg." This is eminently logical. However, in the writer's study of the field exposures, he found evidence to indicate that limestone areas represented inliers of the older limestone formations appearing through the Martinsburg only at the few places noted in Table 1 of the original paper. In other places the limestones do not seem

to be at the base of the Martinsburg and many of them not even near the base. Some of them were formerly referred to the Leesport and others were previously unrecorded. For the reasons originally discussed, these were included within the Martinsburg formation. Intensive study of local areas will undoubtedly uncover new information by which the writer's designations can be verified or disproved. For example, recent detailed work by Willard and Cleaves [3] along the Susquehanna River has indicated that the limestone exposed at Enola is synclinal in structure, and cannot therefore be Leesport as previously mapped. I designated this area as "probably Martinsburg" on other grounds. Stose's field evidence, by which he knows specific areas on which we are in disagreement to be at the base of the Martinsburg, should be presented and will be a welcome contribution to the problem.

(2) The second difference of opinion concerns the nature and extent of the Leesport formation. Leesport has been used in the past to include (a) cement rock, which is argillaceous, non-dolomitic limestone without shale layers or shale partings, and which lies beneath the Martinsburg formation; (b) platy limestones and massive dolomitic limestones with shale partings which seem to be at the base of the Martinsburg, although the evidence for this is not clear to me at all places; (c) platy limestones with shale partings, which lie near but not at the base of the Martinsburg but which include many feet of homogeneous shale; and (d) platy and massive limestones and dolomites with shale partings lying high in the Martinsburg formation. I have recently discussed the "cement rock" areas east of the Schuylkill River, and have correlated these limestones with the Jacksonburg formation of New Jersey.[4] The platy limestones near but not at the base of the Martinsburg, and the platy and massive limestones and dolomites well up in the Martinsburg formation, are the ones for which I have used the term "Martinsburg limestone." This leaves the Leesport formation restricted only to local and discontinuous areas of platy limestones and massive dolomites lying directly at the base of the Martinsburg. The formation thus becomes restricted both horizontally and vertically. However, the previous usage of the term Leesport seems to me to invite confusion, especially in the structural interpretation of the Martinsburg formation.

The second part of Stose's discussion and his geologic map concern eastern areas of Martinsburg limestones near Seemsville in the Allentown quadrangle. In this region, Stose has used the term Leesport to designate the "cement rock" beds which I shall refer to as the Jacksonburg. Stose is quite correct in pointing out that the limestones in this

[3] Personal communication.

[4] Ralph L. Miller: *Stratigraphy of the Jacksonburg limestone*, Geol. Soc. Am., Bull., vol. 48 (1937) p. 1687-1718.

region are areally more extensive than my outcrop map in the original paper indicated. Behre's slate report,[5] to which Stose refers, shows that a number of the limestone outcrops lie along a continuous limestone belt. B. L. Miller, whose map is in part reproduced by Stose (Fig. 3), is in agreement with Behre's later mapping.[6] The writer has revisited the region in question since receiving this discussion and in some of the areas finds no conclusive field evidence by which the extent of the limestone can be delimited. As Stose remarks, exposures are lacking in most of the lowlands north of the "shale boundary as mapped by B. L. Miller." However, the area west of Seemsville can hardly be as extensive as his map (Fig. 3) shows, for shale outcrops do occur centrally in this area between the marginal limestone exposures, and they also occur along Hokendauqua Creek where the presence of limestone is suggested.

I do not know whether the large lowland to the east and southeast of Seemsville is underlain by Jacksonburg cement rock or by Martinsburg shale, as no exposures are present. Proposed geophysical exploration in this region may supply information by which the shale boundary can be determined. However, the boundary as drawn by Stose, essentially following the contours, would imply nearly flat dips over this large area. The structural pattern in this general region, and throughout the entire Lehigh Valley, is one of rapidly changing dips with complex folding and some overturning. Flat-lying, nearly undisturbed beds are rare and extremely local. Because of this structural habit, the shale boundary as mapped by previous workers in the region is remarkably rectilinear, and free from deep limestone embayments cutting across the regional strike, such as those shown in Figure 3.

In studying these limestone areas in the field, the writer has not been able to trace the limestone beds continuously from one exposure to the next, the exposures being limited to the small lenses shown in solid diagonal-lined pattern on Stose's map (Fig. 3). Shale crops out under water in the creek bed directly between the two southernmost lenses of Martinsburg limestone nearly due south of Seemsville. This shale outcrop lies about one-eighth of a mile south of the position in which Stose draws the shale boundary. The relation between the shale outcrop and the western of the two limestone exposures, 150 feet away, also seems to indicate that the shale dips beneath the limestone and therefore that the limestone is not at the base of the Martinsburg.

The topmost beds of the Jacksonburg can be seen in eight places along the section of the main limestone belt covered by Stose's map, and many large quarries and fine exposures from the Schuylkill River to New Jersey

[5] C. H. Behre, Jr.: *Slate in Pennsylvania*, Pa. Geol. Surv., 4th ser., Bull. M16 (1933).
[6] Personal communication.

have been intensively studied by geologists. Everywhere the upper part of the Jacksonburg consists of thin-bedded, black, argillaceous limestone with well-developed slaty cleavage, locally containing *Prasopora orientalis*. This lithology is referred to as the "cement rock." The massive-bedded, dolomitic and siliceous limestones exposed within the shale belt carry *Cryptozoon* and bear little lithologic similarity to the "cement rock." It is difficult to imagine that the upper part of the Jacksonburg formation, which has such uniform character for miles along the strike and across the strike southward, would change its lithology abruptly within a few yards northward, and so completely that quarries north of the shale boundary, exposing from 20 to 50 feet of limestone, contain no beds which resemble the "cement rock."

The only fossils, which have been found in any of the Martinsburg limestones, are the cryptozoons. The preponderance of the field evidence seems to indicate that the limestones belong within the Martinsburg formation.

Structure of the Uinta Mountains. **By J. D. Forrester**

(pages 631-666)

Comment by EDMUND M. SPIEKER*

The Uinta Mountains, early made classic by Powell and studied in part by many later geologists, have long invited thoroughgoing investigation. The paper by Forrester apparently aims to present a fairly complete picture of the structure and geologic history, but it contains little more than a summary of the stratigraphy. Forrester, as expressed in his own words, has little to add to existing knowledge of the rock section, and the main aim of the work is to depict the structure; but some of the conclusions respecting the structure, and especially the succession of dynamic events, are based on stratigraphic and other data that are inadequate. Such conclusions, especially when presented in papers of wide and unified coverage such as this, might easily become rooted in generalizations of the sort that takes years to correct, and Forrester's paper should not pass without comment.

The isopach map (Fig. 1, p. 635) gives a false impression of geosynclinal conditions in the general region, for at least three reasons:

(1) It is difficult, if not impossible, to estimate the Mesozoic part of the section in much of the territory west of the Wasatch Mountains be-

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cause Mesozoic rocks have been largely removed. Forrester apparently has neglected them for much of the region and failed to specify his assumptions where he has included them.

(2) Known thicknesses of Paleozoic rocks are much greater than the values shown on the map for Paleozoic and Mesozoic combined. In the region of the Oquirrh Mountains the isopachs show thicknesses between 15,000 and 17,500 feet, but Gilluly's section,[1] Cambrian to Pennsylvanian, inclusive, is 20,000 to 24,000 feet thick, and the nature of the Permian, Triassic, and Jurassic rocks not far to the east hardly permits the assumption that they were not originally in the Oquirrh region. The effective geosynclinal thickness there at the close of the Mesozoic was certainly more than 25,000 feet, and possibly much more. This criticism applies in general to the western part of the isopach map, which shows the Wasatch geosyncline much more constricted than it was at the close of Mesozoic time and probably not deep enough.

(3) In depicting the geosyncline Forrester omits the pre-Cambrian rocks from the isopach map and gives as his principal reason for doing so that "it may here be assumed that the Proterozoic sediments had essentially the same general distribution as the Paleozoic and thus, if omitted, would not change the present geosynclinal picture" (p. 635-636). Over the whole area shown on this map the thickness of the pre-Cambrian is poorly known, but the few measurements on record do not show uniformity in distribution of the pre-Cambrian and the Paleozoic. In the central Wasatch Mountains the pre-Cambrian sedimentary rocks are 10,000 to 11,000 feet thick, but not far to the south, in the southern Wasatch, they are 500 to 1000 feet thick, and their base is exposed.[2] To the north the basal Cambrian lies on older crystalline pre-Cambrian rocks.[3] Forrester himself mentions Mississippian strata resting on the older crystallines south of the Uintas, near Moab (p. 636). The pre-Cambrian quartzite may be uniform along the Uinta axis, and its omission may make no difference there, but in the regional picture there is bound to be a difference, as the facts just given demonstrate. Assuming that the configuration of the crystalline basement was dynamically the significant feature of the geosyncline, it seems probable that addition of the pre-Cambrian sedimentary rocks to the map would change its significance, in contrast to Forrester's assumption that it would not.

Forrester (p. 640) refers to "terra cotta" beds overlying the Twin Creek formation and speaks of them as "typical Morrison of the Uinta Mountain

[1] James Gilluly: *Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah*, U. S. Geol. Surv., Prof. Paper 173 (1932) p. 6-38.

[2] A. J. Eardley: *Stratigraphy of the southern Wasatch Mountains, Utah*, Michigan Acad. Sci., Arts, Letters, Papers, vol. 18 (1933) p. 312-313.

[3] B. S. Butler, G. F. Loughlin, V. C. Heikes, *et al.: The ore deposits of Utah*, U. S. Geol. Surv., Prof. Paper 111 (1920) p. 77.

region." He gives no description of the Twin Creek, and it is difficult to deal with his section, but unless I am mistaken these "terra cotta" beds, far from being distinctive of the Morrison formation, are thoroughly characteristic of the uppermost marine Jurassic of the general region—for example, the Summerville formation of the San Rafael group. Some of them are more like the Entrada formation, and their position in this part of the Jurassic section is uncertain; but they occur throughout southern, central, and eastern Utah in the upper part of the unit approximately equivalent to the San Rafael group, and they are by no means typical Morrison.[4] There is typical Morrison in the section on Duchesne River, on the south flank of the Uintas, but as I have seen it this Morrison overlies the beds of "terra cotta" type (a good descriptive term) and is distinct from them in both lithology and origin.

The principal criticism I have to make of the stratigraphic element in this paper concerns data that are used to determine the ages of orogenic movements. Forrester concludes that the Uinta and Wasatch belts were folded at the same time—in the Laramide orogeny, at the close of the Cretaceous; he derives this conclusion from four points, two of which are stratigraphic (p. 654): "(1) Laramie deposits are absent from all places in the Uintas where they might be expected," and "(2) Wasatch (Eocene) sediments are in marked unconformity with the Mesaverde group and, in a few places, with the Montana group of the upper Cretaceous."

The first of these is a rather bold statement to appear in a work that does not present a detailed study of the stratigraphy. It may be true, and I am not prepared to assert the converse, but after reconnaissance observation of the section in the Tabby Mountain district I should hesitate to say flatly that "Laramie deposits" are absent; I rather incline to the belief that they are present. The term "Laramie deposits" I assume to mean strata of latest Cretaceous age, approximately equivalent to the Lance, or *Triceratops* beds; in view of the confusion that has invested this term, and the prime importance of the beds involved in working out the Cretaceous-Tertiary history, the term should be defined before it is used. If beds of this age are absent, nothing is proved except that the folding is no older than the youngest beds now recognized in the disturbed mass—namely, the Mesaverde—and this interpretation leaves a considerable part of late Cretaceous time in which the folding might have taken place; in fact, it is obvious, that to prove that the folding occurred at the end of the Cretaceous, it would be necessary for beds of Laramie age, as here defined and as interpreted by most students of the problem, to be present, not absent.

[4] Similar beds in the upper part of Parley's Canyon, east of Salt Lake City, have been identified as Morrison by A. A. L. Mathews [*Mesozoic stratigraphy of the central Wasatch Mountains*, Oberlin Coll., Lab. Bull., n.s., vol. 1 (1931) p. 47].

The second statement involves, of course, identification of the Wasatch formation. Forrester states (p. 641) that for the Tertiary part of the section he follows Kay's interpretation,[5] and, further, that Kay regarded Lupton's estimate of 10,000 feet for the Wasatch formation on Duchesne River as excessive, implying (although Forrester's statement is somewhat ambiguous) that Kay identified Wasatch strata there. Actually, Kay stated his opinion that the beds in question are not Wasatch, but rather Uinta, in age. My own judgment, based on reconnaissance examination of scattered areas along the south flank of the mountains and in the Uinta Basin, is in agreement with that of Kay; it is unlikely that beds of Wasatch age are present on the southern margin of the mountains. If they should be present, there is still the notable part of the Tertiary column represented by the Fort Union beds, or the Puerco and Torrejon, to be accounted for. Stratigraphic evidence, as far as it has been worked out, shows that the first episode of folding in the Uinta Mountains occurred at some time between the Montana epoch of the Upper Cretaceous and the Uinta epoch of the Eocene, a stretch of time too long to support the conclusion that the folding was simultaneous with that of the Wasatch Mountains or that it occurred at the end of the Cretaceous.

For the remainder of his evidence that the Uinta and Wasatch Mountains were folded at the same time, Forrester gives structural facts: "The Uinta Mountain type folds project into the Wasatch Mountain area," and "The trends of minor structures swing from Wasatch Mountain trends to Uinta Mountain trends and *vice versa*" (p. 654). This evidence is not convincing. Folds produced in two separate epochs of compression, one east-west and the other north-south, would exhibit such features of relationship, as can easily be seen in simple experiments with piles of cloth or damp tissue paper. In fact, as far as the argument based on mechanics is concerned, the known Laramide movements in the Wasatch and Uinta lineaments are much more logically explained by separate, than by simultaneous, orogenic epochs, for which a somewhat unusual, if not improbable, distribution of stresses would be necessary. It is possible that a careful analysis of structural detail, in terms of known dynamic principles, would yield evidence of superposition or the lack of it, but the data offered by Forrester are inadequate for any such demonstration. Neither the stratigraphic nor the structural evidence presented proves simultaneity of deformation in the Uinta and the Wasatch, and the precise age of the folding is still unknown.

It seems curious in connection with this aspect of Uinta history that Forrester does not mention the conclusion reached by Calkins,[6] after

[5] J. L. Kay: *The Tertiary formations of the Uinta Basin, Utah*, Carnegie Mus., Ann., vol. 23 (1934) p. 357-372.

[6] F. C. Calkins, *in* Butler *et al.*: *op cit.*, p. 251-254.

analysis of the available facts, that the Wasatch folding is notably older than the Uinta. It is possible to be sure, that the movement recognized by Calkins was later than the first in the Uinta belt, but it was not so specified by him, and any view of the structural relationships divergent from that of Calkins should be fortified by some disposition of his apparently sound argument. It might also be noted that in the discussion of the westward continuation of the Uinta axis, a question that has engaged many geologists in lively debate, the summary of the evidence given by Gilluly [7] is not mentioned.

In his determination of the age of the second movement in the Uinta belt, which he interprets as a strong vertical uplift, Forrester invokes evidence similar in general character to that for the first. He dates this movement as late Eocene or early Oligocene, giving as evidence (p. 659) "close association of the marked warping with the intrusive bodies of late Eocene or early Oligocene age in the Wasatch Mountains," and (p. 660) ". . . warping and displacement of Eocene sediments, and not of Oligocene formations, as, for instance, on the south flank of the range. . . ." The age of the Wasatch intrusives is fixed as follows (p. 642):

"The flows cover lower Eocene sediments and are older than Miocene. They are, therefore, placed in late Eocene and early Oligocene time, which is essentially in accord with conclusions reached by Dutton,[83] Butler,[84] and Boutwell.[85] From the nature of the extrusives, they appear to be genetically related to the intrusive rocks of the central Wasatch Mountains, with which they are essentially contemporaneous."

[83] C. E. Dutton: *Report on the geology of the high plateaus of Utah*, U. S. Geol. Surv. Rocky Mtn. Reg. (1880) p. 55.
[84] B. S. Butler, *et al.*: *The ore deposits of Utah*, U. S. Geol. Surv., Prof. Paper 111 (1920) p. 99.
[85] J. M. Boutwell: *Geology and ore deposits of the Park City district, Utah*, U. S. Geol. Surv., Prof. Paper 77 (1912) p. 70, 93-94.

Passing over the inadequacy of the first facts to place the flows exactly in the Eocene-Oligocene transition, one gets the impression from the second statement that the three authors cited assigned approximately similar age to the extrusives. On the contrary, Boutwell simply said they are later than Eocene, and Butler merely offered comment on a quotation from Dutton, who concluded that the volcanic activity began in the late Eocene and continued almost to the present day. Further, the volcanics placed by Dutton in the late Eocene are propylitic and were followed after a long time interval by the andesites of the High Plateaus. As a matter of fact, Dutton's basis for the late Eocene age of the oldest volcanics was very meager and was based on theoretical considerations that cannot be reviewed here. Subsequent regional work has revealed volcanic activity in the early Tertiary but not the type of volcanism represented by the flows west of the Uinta Mountains. Although he was at some pains to emphasize that the age terms used had little exact

[7] James Gilluly: *op. cit.*, p. 71-73.

meaning, Dutton expressed his opinion [8] that the bulk of the volcanics of central and southern Utah, including the rock types comparable with those of the Uinta region, are of Miocene or early Pliocene age. These older works, in any event, have only suggestive bearing on the age of the Uinta volcanics. The volcanic history of the region as a whole was long and complex. Forrester's statement that the flows are older than Miocene appears to be unsupported by anything I can find in the paper. It is doubtless meant that they are older than the Bishop conglomerate, which is probably Miocene, but I find no place on the geologic map where Bishop overlies the volcanics.

The relations between the intrusives and warping is the only element in the picture that is well established. The relation between intrusives and extrusives is by no means settled. Divergent opinions have been expressed, and, even if a majority of the opinions should favor contemporaneity, the relation cannot be treated as established. Reasoning based upon the relationships among these three elements—the extrusives, the intrusives, and the warping—should lead to nothing stronger than a suggestive statement.

The other evidence—the relation between the Eocene and the Oligocene formations—is not conclusive, at least as given by Forrester. The Uinta and Duchesne River formations, to judge from the work of Peterson and Kay and from my own observations, are virtually indistinguishable except on the basis of their vertebrate faunas. It is not clear from Forresters' statement that they are anywhere separated by angular unconformity, and, barring such evidence, the mere fact that the Eocene beds dip more steeply proves nothing, unless it is shown that structural conditions demand the equivalent of angular unconformity. If there is any place where Eocene beds have been strongly disturbed in such position as to have required the deformation of nearby Oligocene that is not so disturbed, such occurrence should be described sufficiently to leave no doubt in the reader's mind as to the nature of the evidence. I stress this point, because I doubt that any such proof has been found.

Returning for a moment to the question of the older movement, Forrester compares the situation in the main body of the Uintas with that in the Axial Basin (p. 654, 655), where the entire succession up to, and including, the Green River formation is involved in the folding and the Wasatch formation overlies the post-"Laramie" without angular unconformity, and, because, in his opinion, this shows the Axial Basin fold to be later than the Uinta, he rules the Axial Basin out of "the true Uinta Mountain structure." Here is a confusion of time and tectonic values. If

[8] C. E. Dutton: *Report on the geology of the high plateaus of Utah*, U. S. Geol. Geog. Surv. Rocky Mtn. Reg. (1880) p. 231.

the Axial Basin fold were tectonically distinct from the Uinta, such separation would have significance, but it is so characteristic a prolongation of the Uinta Mountain arc, forming the connecting link with Rocky Mountain trends in western Colorado, that to exclude it from the Uinta structure serves no valid need. Even if it was folded after the main Uinta belt, it is still part of the Uinta structure, and, as may be seen from the foregoing discussion, the valid evidence on the Uinta folding does not exclude the possibility that the two were contemporaneous.

There are other matters in the paper that might bear discussion, but I shall mention only one more. On his geologic map, Forrester shows the Mesaverde formation cut out just west of the Utah-Colorado boundary, presumably by overlap of the Tertiary beds, to judge by interpolation between his cross-sections; for the district southeast of Vernal, he shows Mancos overlain by Tertiary beds. All earlier workers known to me have identified the Mesaverde formation in this stretch; in fact, Tolmachoff [9] has reported Upper Cretaceous fossils, interpreted by him as Mesaverde, from the asphalt-bearing beds formerly thought to be Eocene.[10] If Forrester had any evidence against the recognition of Mesaverde in this section, he should have stated it. He says (p. 640) that the Mesaverde of the east grades imperceptibly into the upper Frontier of the west, but there is certainly no such relationship in the Vernal district, and the strata there mapped in the past as Mesaverde are far above the true Frontier of the west. From my own knowledge of the area, and in terms of the principles generally accepted to govern stratigraphic nomenclature, I can see no conceivable basis for mapping the sandstones at the base of Asphalt Ridge as Mancos.

Reply by J. D. FORRESTER

The writer welcomes this opportunity to answer Dr. Spieker's comments and to explain certain features more fully than the necessary brevity of his original paper would permit.

The primary purpose of the paper is given at the bottom of page 632, and I find no reason to repeat the statement here. My own words concerning the stratigraphy are not as Spieker states, but are as follows (p. 637); "Inasmuch as the stratigraphy has been discussed by Emmons, Powell, Berkey, Weeks, Veatch, Sears, Gale, Boutwell, Hancock, Schultz, Stanton, Rich, Kay, Heaton, and many others, it is not necessary to repeat detailed descriptions. During the writer's field work, however, certain interesting features were noted, and of these the more important will be discussed."

[9] I. P. Tolmachoff: *Discovery of Upper Cretaceous fauna in the Asphalt Ridge, Utah* (abstract), Geol. Soc. Am., Bull., vol. 44 (1933) p. 103.

[10] E. M. Spieker: *Bituminous sandstone near Vernal, Utah*, U. S. Geol. Surv., Bull. 822 (1930) p. 81.

Dr. Spieker is correct concerning Mesozoic sedimentary thicknesses in the region west of the Wasatch Mountains; in fact, information on Paleozoic thicknesses is not abundant. Spieker infers that this area was not studied when the isopach map was made and criticizes the writer for neglecting the region. More data points were not established and the map was not enlarged westerly because sufficient reliable information on Paleozoic and Mesozoic sections was not available. The various localities at which thicknesses were determined are clearly shown on the isopach map, and these data are not assumed. The only assumptions are in interpolating the isopach lines, which, as far as the writer knows, must be done on any contour map.

Gilluly's[11] excellent work was not used in calculating sedimentary thicknesses, for two reasons: (1) Combined Mesozoic and Paleozoic sections were not present; (2) the major variation, which causes an abnormal sedimentary thickness in the region, is localized and much constricted. For instance, Gilluly [12] says that "the area subject to this great sedimentation (*Pennsylvanian*) was probably rather small, as none of the other districts that have been studied in the region have shown thicknesses even remotely approaching this." Dr. Spieker would assume a certain thickness for Mesozoic sediments in the area, whereas assumptions such as this were avoided during the study.

It is important in making such a compilation of geosynclinal sediments that an attempt be made to use only data from points established in areas where erosion has not reduced the original or primary sedimentary thicknesses—that is, to use thickness data which are equivalent to depositional values,—otherwise, the geosynclinal definition and limits cannot be determined. Spieker's general statement that the isopach map is in error in the western part should be, as has been brought out, emended to include only the very constricted area described by Gilluly. Near the eastern edge of the Fairfield quadrangle the thicknesses shown on the map are 20,000 feet or more and not from 15,000 to 17,500 feet (as stated by Spieker).

My authority for concluding that the "Cordilleran geosyncline was probably in existence during the Proterozoic era and probably in the same position as during Paleozoic time" (p. 635) is from Schuchert and Dunbar.[13] Other writers have also proposed similar conditions. This conclusion is only one of the reasons given for omitting the pre-Cambrian geosynclinal sediments from the isopach map and is not necessarily the principal one (p. 636).

[11] James Gilluly: *Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah*, U. S. Geol. Surv., Prof. Paper 173 (1932) 171 pages.

[12] *Op. cit.*, p. 38.

[13] Charles Schuchert and C. O. Dunbar: *Textbook of geology*, Part II (1933) maps of Cordilleran geosynclines, 551 pages. John Wiley and Sons, New York.

Spieker cites works [14] which he contends disprove the statement that disuse of the pre-Cambrian sedimentary thicknesses in compiling the isopach map is justified. Here again, he is evidently unaware of the fact that we are dealing with rock thicknesses only in their relation to previous geosynclinal troughs and, therefore, his citation of areas in which erosion (as stated by the cited authors) undoubtedly has reduced the thicknesses, is unwarranted. It does not prove that the suggested thickness (12,000± feet) was not originally present, but it does sustain my contention that high-land areas were in existence for certain periods and that there were variations in sedimentation from time to time within the limits of the Rocky Mountain Geosyncline as a whole (p. 634).

It is clearly stated (p. 636) that if the Algonkian sediments were used in the geosynclinal picture, the Uinta Trough would probably be accentuated or deepened. Regardless of how it *seems*, the fact remains that the Uinta geosyncline received sediments without marked warping or folding from the Archean to the Laramide Revolution and was a localized "deep", in total section, compared to the regions to the north and south.

I do not speak of the "terra cotta" beds as overlying the Twin Creek formation. My statement is that these beds are stratigraphically under the Aspen and Dakota formations; that is, as the term "terra cotta" is used, the beds are certainly not under Spieker's Morrison of the Duchesne River area. They represent, instead, upper Morrison members and are characteristically continental deposits and not marine in origin.

I state that the folding of the Uinta and Wasatch ranges was contemporaneous and represents Laramide deformation *near* the close of the Cretaceous (p. 649), and not, as Spieker says, "at the close of the Cretaceous." This differentiation is important inasmuch as it is the basis of much of his argument. Comprehensive studies show conclusively that the Laramide Revolution had its inception in late Cretaceous time. For instance, Schuchert [15] demonstrates that the revolution started at essentially the close of Comanchian time and persisted to at least the beginning of the Eocene.

The term "Laramie" has been used in the same sense (uppermost Cretaceous) as described in cited reports by Gale [16] and later by Sears [17] and, therefore, need not be redefined.

With the inception of Uinta folding in pre-Laramie time the deposition of typical Laramie beds necessarily could not reasonably have occurred

[14] A. J. Eardley: *Stratigraphy of the southern Wasatch Mountains, Utah*, Mich. Acad. Sci., Arts, Letters, Papers, vol. 18 (1933) p. 312-313.
B. S. Butler *et al.*: *The ore deposits of Utah*, U. S. Geol. Surv., Prof. Paper 111 (1920) p. 77.

[15] Charles Schuchert: *A textbook of geology*, Part II (1915) p. 442. John Wiley and Sons, New York.

[16] Hoyt S. Gale: *Coal fields of northwestern Colorado and northeastern Utah*, U. S. Geol. Surv., Bull. 415 (1910) p. 72-74.

[17] J. D. Sears: *Geology and oil and gas prospects of part of Moffat County, Colorado, and southern Sweetwater County, Wyoming*, U. S. Geol. Surv., Bull. 751-G (1924) p. 291.

in the Uinta region proper. It was probably a time of neither widespread erosion nor marked deposition in the Uinta Mountain area. The folding stresses and consequent uplift undoubtedly persisted over a considerable length of time, and the absence of certain formations, which were deposited elsewhere during the uplift, is concisely explained by Schuchert.[18] The writer has discussed briefly such a phenomenon under the title "Post-Folding Erosional History" (p. 655-656).

Kay,[19] in discussing the Tertiary rocks of the Uinta region with me, was of the opinion that there are probably Wasatch (Eocene) sediments in the western part of the Uinta Mountain area but certainly not a thickness of 10,000 feet outcropping along the Duchesne River. My statement (p. 641) is that Kay's interpretations of the Tertiary rocks along the *south flank* were followed. This is important, because Wasatch (Eocene) sediments have been determined at various localities along the north flank of the range. Wherever observed, the Wasatch beds are in marked angular unconformity with Cretaceous sediments. Spieker says that his "judgment . . . is in agreement with that of Kay; it is unlikely that beds of Wasatch age are present on the southern margin of the mountains." Kay,[20] however, shows Wasatch sediments in T. 6 S, R. 25 E, near Jensen, Utah. Spieker has neglected entirely the Tertiary rocks along the north flank of the Uintas and bases his generalizations concerning the time of folding on a consideration of limited areas. Bradley,[21] in a study published as my paper was being submitted for publication, notes Wasatch (Eocene) sediments on the north flank of the range and concludes that the pre-Tertiary rocks of the Uintas had essentially their present attitude at the end of the Cretaceous period. Bradley evidently postulates Laramide uplift.

Dr. Spieker dogmatically states that the closely associated strains of the Wasatch and Uinta ranges can be explained most readily by supposed stresses acting in separate orogenic epochs. He infers that I have neglected a study of the mechanics of the folding and have thus arrived at an answer which is opposed to dynamic principles. His argument of the mechanics of the stress relations is based on "simple" experiments with *piles of cloth* or *damp tissue paper* and these, he evidently thinks, are comparable to natural tangential and deep-seated stresses acting on 35,000 ± feet of geosynclinal sediments. Field work proves that Spieker's generalizations are unwarranted. For instance, Spieker, citing Calkins,[22] and sug-

[18] Charles Schuchert: *op. cit.*, p. 451.

[19] J. LeRoy Kay: oral communication (1934).

[20] J. LeRoy Kay: *The Tertiary formations of the Uinta Basin, Utah*, Carnegie Mus., Ann., vol. 23 (1934) pl. 45.

[21] W. H. Bradley: *Geomorphology of the north flank of the Uinta Mountains*, U. S. Geol. Surv., Prof. Paper 185-I (1936) p. 167, pl. 34.

[22] F. C. Calkins, *in* B. S. Butler *et al.*: *op. cit.*, p. 251-254.

gesting the presence of Laramie sediments and the absence of Wasatch rocks in the Uinta Range, infers, although he does not so state directly, that he believes that the Uinta folding was later than that of the Wasatch Mountains. In other words, his mechanics permit him to assume that the intense northward-striking folds of the Wasatch Range would be obliterated by later Uinta stresses along the projection of the Uinta axis into the Wasatch area and that the formations would readjust themselves and swing around to take the more or less broad, uniform eastward trends which they now exhibit. This is presupposing, of course, that, if the Wasatch Mountains were folded first, the relatively close northward-trending folding in the range to the north and south of the projection of the Uinta axis would also have been present in the projected axial area. The strong, tangential stresses which acted on the Wasatch Range, as a whole, suggest that such a supposition is proper.

The stratigraphic and structural evidence supporting my conclusion concerning the age of the first Uinta folding, as given in the original paper, and elaborated upon here, still pertains. The Uinta and Wasatch ranges were folded contemporaneously during the Laramide Revolution.

Calkins' suggestion [23] of the origin and time of uplift of the Uinta Range is similar to that proposed by Beeson. Beeson's work was cited and discussed in my original paper.

Billingsley [24] and several others have found occasion to deal with the Uintas in a general or broader sense. Inasmuch, however, as field work brought out certain salient facts concerning the structural relationships of the range, and as space was limited, the writer did not, nor does he now feel obligated to, indulge in a lengthy discussion of all previous theories and hypotheses.

Dr. Spieker has apparently mis-read that the age of the *Wasatch intrusives* is discussed on page 642. *Extrusive* igneous rocks in the western end of the *Uinta Mountain* region are there considered to be late Eocene and early Oligocene in age.

Butler [25] not only offers comment on a quotation from Dutton, but cites Boutwell's paper and states that Boutwell and Woolsey believe that the central Wasatch intrusives are genetically related and essentially contemporaneous with the andesitic extrusives of the western end of the Uinta Mountains. With such a statement, Butler is in accord; in fact, he elaborates upon the extrusive-intrusive relationship.

The andesites are considered to be older than Miocene, because the

[23] *Ibid.*

[24] Paul Billingsley: *The Salt Lake region*, 16th Internat. Geol. Congr., Guidebook 17, Excur. C-1 (1933) p. 19-24.

[25] B. S. Butler *et al.*: *op. cit.*, p. 99.

North Flank Fault (Pl. 3) which cuts them, at least in part, apparently does not along its extent offset the Bishop (Miocene) formation.

I do not read that Dutton [26] necessarily suggests the Miocene or Pliocene age of the andesitic extrusives. His statement is to the effect that the hornblendic propylites and andesites are in upper Eocene, and are succeeded by later augitic andesites after an erosional interval. Dutton [27] postulates that the oldest extrusives (tufas) are middle Eocene followed by propylites which were in turn followed by andesitic material after a long period of erosion. This, to my mind, does not preclude the suggestion that the andesites are Oligocene.

Near the southern margin, or, in other words, along the south flank of the Uinta Range, the Eocene formations have been abruptly warped and dip southward. This flexure, when considered with respect to the adjacent range and the attitude of these formations in the Uinta Basin region not far to the south, is certainly excessive for primary or original dip. It suggests that warping or tilting occurred after upper Eocene time. Dr. Spieker [28] has reached a similar conclusion. Other evidence (p. 658), together with the fact that this warping is so marked along the extreme margin of the Uinta Range, indicates that the beds were tilted because of uplift of the range rather than through subsidence of the basin region. The Duchesne River (Oligocene) formation, on the other hand, in localities north of this flexure of Eocene rocks and, therefore, farther within the flanks of the range, where the uplift occurred, has not been tilted in any degree commensurate with that undergone by the older Tertiary formations. Kay,[29] for instance, shows relatively horizontal Duchesne River rocks overlying abruptly flexed older formations near the Mesozoic-Tertiary contact. During field work, the Duchesne River formation was noted, northeast of Vernal, Utah, overlying folded Cretaceous rocks (Pl. 3).

This structural evidence supports the conclusion that uplift occurred after deposition of Eocene beds and before Duchesne River (Oligocene) time.

The Axial Basin region was folded after Eocene time [30] and, therefore, at a later time than the first Uinta Mountain uplift. It is certainly tectonically distinct from the first Uinta folding uplift. The writer has shown here, as well as in the original paper, that there is no confusion of time or tectonic values and that a separation of the Axial Basin folding from the Uinta folding is significant in that it delimits the eastern end of the Uinta uplift through Laramide folding stresses. Such a conclusion is certainly

[26] C. E. Dutton: *Report on the Geology of the high plateaus of Utah*, U. S. Geol. Geog. Surv. Rocky Mtn. Reg. (1880) p. 231.
[27] *Op. cit.*, p. 55-56, 229.
[28] E. M. Spieker: *Bituminous sandstone near Vernal, Utah*, U. S. Geol. Surv., Bull. 822 (1930) p. 82.
[29] J. LeRoy Kay: *op cit.*, pl. 47.
[30] J. D. Sears: *op. cit.*, p. 300.

valid. Regardless of Spieker's statement to the contrary, the writer does not exclude the Axial Basin region from Uinta Mountain structure, in general. The writer says (p. 632), "As a structural element, the Uinta Range is a prominent feature of the Rocky Mountain system. . . . Eastward, its anticlinal axis extends through the Axial Basin uplift into the Grand Hogback, which has a north-south trend." (See also p. 654, 655, 659.)

The necessary drafting methods employed, in order to reduce the original maps to a size suitable for publication, did not afford the opportunity to show many details and narrow rock exposures as noted in the field (p. 633). Unfortunately, the Mesaverde formation outcrop cited by Dr. Spieker, in the area near Vernal, Utah, is subject to that limitation. It seemed advisable to adopt such a procedure rather than to attempt a measure or symbol which would be illegible and tend toward confusion on the maps.

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